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VALUE OF BITUMINOUS COAL AND COKE FOR GENERATING STEAM IN A LOW-PRESSURE CAST-IRON BOILER

BY

C. E. AUGUSTINE, JAMES NEIL, and
WILLIAM M. MYLER, Jr.

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VALUE OF BITUMINOUS COAL AND COKE FOR GENERATING STEAM IN A LOW-PRESSURE CAST-IRON BOILER

By C. E. Augustine, James Neil, and William M. Myler, Jr.

INTRODUCTION

Since its establishment, the Bureau of Mines has been conducting tests and investigations for the increase of efficiency in the utilization of fuels for steam boilers. This report is the second of a series dealing with the combustion, at low rates, of various typical fuels in boilers and furnaces suitable for heating large buildings, and may be considered a companion work to Technical Paper 303.[1] The tests reported in this paper were conducted during 1922 and 1923 at the Pittsburgh experiment station of the bureau.

Although the value of a fuel for the generation of steam depends largely on its heat content, its behavior in burning, and the thermal efficiency of the boiler, variations in the efficiency obtained may be caused by many factors, such as rate of steaming, furnace and grate design, volume of combustion space, arrangement of heating surfaces of the boiler, method of firing, method of supplying air, and kind and size of fuel.

The boiler used in these tests was made of cast-iron sections and was designed for heating large buildings. The practice of heavy firings at fairly long intervals, which is employed with this size of boilers in most buildings, was followed in these tests. The firing charge was about 150 pounds; therefore the firing period was varied to suit the rate of steaming. Furnace conditions were regulated by adjusting air admission, as indicated by gas analyses, in an endeavor to burn the coal with low heat losses and to avoid either high excess air or combustible in the flue gases, also to make as little smoke as possible.

The bituminous coal was fired by a modified coking method, known as the "center" method. The hot coals on the grate were "cradled"—that is, partly drawn forward and partly pushed back—and the fresh coal was put on the thin fuel bed left across the middle of the grate. The coke was fired by the "spreading" method. The grate length used, up to and including test 10, was 70 inches, but in all the later tests it was reduced to 60 inches. The total number of

[1] Blizard, John, Neil, James, and Houghten, F. C., Value of coke, anthracite, and bituminous coal for generating steam in a low-pressure cast-iron boiler: Tech. Paper 303, Bureau of Mines, 1922, 56 pp.

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sections in the boiler was 12 in all tests; 11 sections were 10 inches wide and 1 was 5 inches wide.

To ascertain the effect on combustion and smoke emission, both wing walls and checkerwork of fire brick were used for mixing the furnace gases in the combustion chamber in the tests with bituminous coal.

ACKNOWLEDGMENTS

The International Heater Co. of Utica, N. Y., lent to the Bureau of Mines the boiler that was used in the tests. It is shown in Plate I.

The tests were planned and made under the direction of John Blizard, formerly fuel engineer for the Bureau of Mines. This report was made under the direction of H. W. Brooks, fuel engineer, and O. P. Hood, chief mechanical engineer, of the Bureau of Mines. R. A. Sherman, A. Pincus, J. K. Seabright, W. M. Myler, jr., M. L. Orr, R. J. Hinch, J. F. Gardner, F. Wentzel, jr., J. P. Stein, C. Schramm, and H. Berg assisted at various times in carrying out the tests.

The composition and calorific value of the coal and combustible content of the ash and refuse were determined in the coal laboratory at the Pittsburgh experiment station under the direction of H. M. Cooper.

PURPOSE OF THE TESTS

The main purpose of these tests was to obtain further information on the relative steaming values of coke and bituminous coals burned in a hand-fired low-pressure cast-iron boiler of a size suitable for heating large buildings. Large quantities of coal were fired at rather long intervals, approximating the practice of firing that would be followed by firemen or janitors in office or apartment buildings and in schools.

Another purpose of the tests was to separate the heat losses, in order to determine the effect of the method of firing and of structural changes in the boiler, when the boiler was operated at ordinary capacities. As this boiler had somewhat smaller gas passages or flues than the usual cast-iron boiler of the same capacity, a survey of temperatures along the path of the gases was made and gas samples and draft readings were taken to obtain data on this arrangement of heating surfaces.

CHIEF RESULTS OF THE TESTS

A brief summary of the results appears below. Detailed results of the tests are given and discussed on later pages.

1. Tests were made at various rates of steaming with Pittsburgh lump coal, Lower Kittanning coal, and by-product coke. The calorific value of the Pittsburgh high-volatile lump coal ranged from

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13,150 to 13,750 B. t. u. per pound; that of the coke from 11,720 to 11,890 B. t. u.; and that of the Lower Kittanning medium-volatile coal from 12,970 to 13,570 B. t. u. This variation is believed to be due partly to variations in moisture content and to sampling. The bituminous coals contained less ash than the coke, about the same amount of moisture, and naturally much more volatile matter. As the Lower Kittanning coal was of smaller size than the coke or the Pittsburgh coal, it packed when fired, causing greater resistance to the flow of air through the fuel bed; also it required more frequent attention by slicing or breaking up the fuel bed to maintain the rate of burning desired. The fuels with the higher ash content, of course, required the removal of more refuse from the grate; the percentage of clinker was highest with coke.

2. At low ratings the bituminous coals and coke were of about equal steaming value; at medium and higher ratings the coals evaporated more water than the coke. The by-product coke had a steaming value about 90 per cent of that of the bituminous coals at the higher ratings. When coke was burned at a low rating the over-all efficiency was high—about 76 per cent—but at the higher ratings this efficiency was less than that of the bituminous coals, being about 66 per cent.

3. The thermal efficiencies ranged from 65 to 74 per cent for Pittsburgh coal, and showed considerable variation at the high ratings. The thermal efficiencies with Lower Kittanning coal ranged from 66 to 72 per cent. The rate of heat absorption, in British thermal units transferred to water per square foot of heating surface per hour (computed values ranging from 3,400 to 10,000), is believed to be higher in these tests than in usual practice with cast-iron boilers. The boiler was operated at higher capacity than in the usual installation recommended by the builders, and the high flue-gas temperature with Pittsburgh coal was obtained with a lower supply of excess air. Because of the higher volatile content of this coal the flames were longer, and less of the heating surface in the flues had a chance to absorb the heat before the gases left the boiler.

4. Other factors being unchanged, the nearer to the fuel bed the secondary air is supplied and the more thoroughly it is mixed with the rising combustible gases, the sooner the combustion will be completed and the larger the proportion of heat absorbed by the heating surfaces from the products of combustion.

5. The pressure drop of air through the fuel bed was about the same for coke and Pittsburgh coal, and was about half of that required for equal ratings with Lower Kittanning coal.

6. The Lower Kittanning coal was slower to ignite and burn than the Pittsburgh coal and showed a tendency to form dead spots and air holes in the fuel bed; it burned unevenly and required much more attention than either of the other fuels.

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METHOD OF CONDUCTING TESTS

The method of conducting the tests was as follows:

1. All of the steam from the boiler was exhausted outside of the laboratory building through an orifice box, which had provision for changes of orifices of $3\frac{11}{32}$, 3, $2\frac{5}{8}$, and $2\frac{1}{8}$ inches in diameter, to suit the desired rate of evaporation. By control of the steaming rates with draft changes to suit the necessary rate of combustion, a gauge pressure of 2 pounds, as near as possible, was carried in the box. Tests were run with coke, and with Pittsburgh and Lower Kittanning bituminous coals, with a steam flow corresponding to about 125, 100, 75, and 50 per cent of the rated capacity of the boiler.

2. During each test reported about 6,000 pounds of fuel was fired, except in three tests when operating conditions made a shortened run advisable. As previously stated, for the entire series, 150 pounds of fuel was used at each firing, except in a few instances when it was best to fire a little more or less than that amount. The firing period was varied to suit the rate of steaming; at the lowest rate the period was 60 minutes and at the highest rate 20 minutes.

3. Coke was fired by the "spreading" method.

4. The Pittsburgh and the Lower Kittanning coals were fired by the "center" method. In each half-hour firing period the surface of the fuel bed was levelled with a rake or hoe about 20 minutes after the firing. Lower Kittanning coal required more frequent breaking-up or slicing than Pittsburgh coal burned at the same rates.

5. Each test started and stopped with a fairly thin fuel bed, the "continuous-firing" method being used, in order to duplicate, within a reasonable limit of error, the fuel on the grate at start and close. The fuel burned in each test was weighed on platform scales before it was fired, and during the test a sample was collected for analysis.

6. The ash and refuse taken from the ash pit and from above grates when fires were cleaned were weighed, mixed, and sampled for analysis.

7. The water fed to the boiler was weighed; both the suction tank and the boiler gauge-glass were calibrated to show the weight of water in tank and boiler. The water level was kept as constant as possible.

8. The steam leaving the boiler passed through a 5-inch vertical steam separator, and the water removed from the wet steam was weighed hourly. For these tests the steam leaving the separator was assumed to be dry saturated steam. In no test did the water separated exceed 1.8 per cent of that fed to boiler.

9. The steam pressure, feed-water temperature, and the draft, air, and flue-gas temperatures were read every 15 or 30 minutes during the tests. The draft, or pressure difference of gases inside the furnace and of the air at the same height outside, was measured

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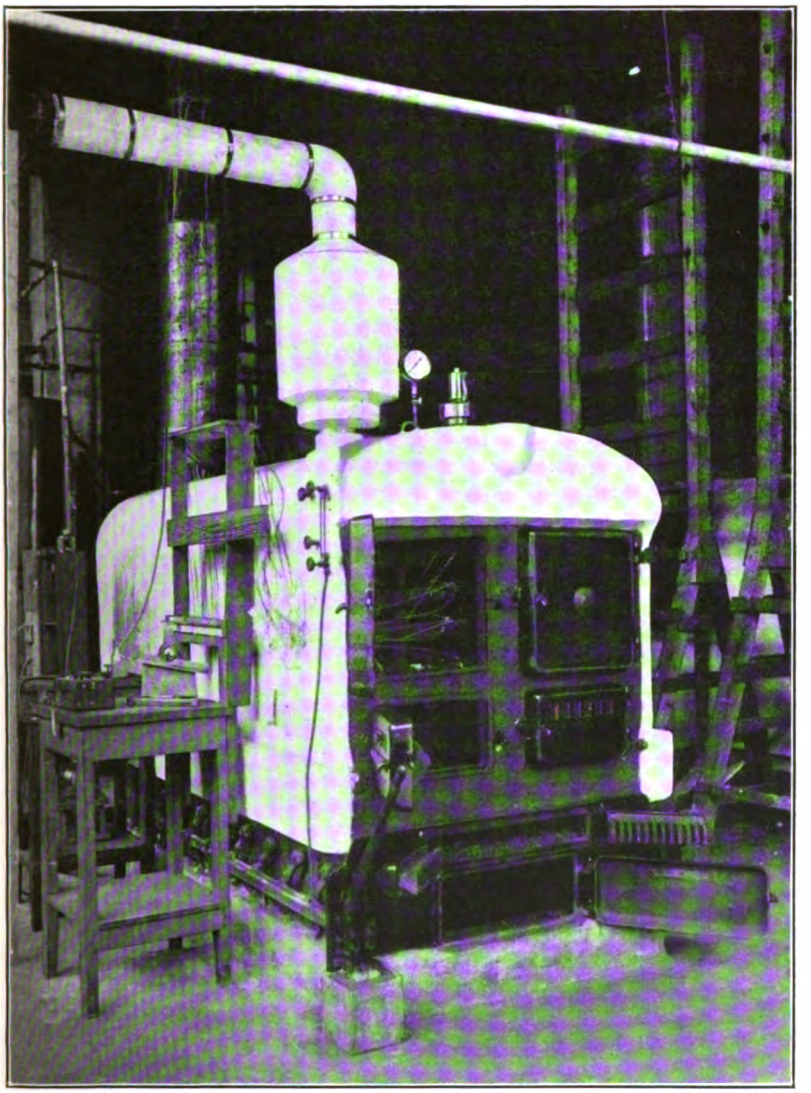

BOILER USED IN TESTS

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by observing the distance between the menisci of gasoline in a U tube that could be inclined to read to 0.001 of an inch of water. In all tests, draft measurements were made in the ash pit and furnace, and below the damper in the flue leaving the boiler, at the points shown by small circles in Figures 2 and 3; in some tests the measurements were made at additional points, as indicated later, in the path of the gases between the furnace and the flue.

DETAILS OF BOILER

The boiler is cast iron, of the sectional type, and is listed by the manufacturer as No. 111–47. Details are as follows (see also Pl. I):

Details of boiler

Length of grate (tests 2 to 10, inclusive), inches	70
Length of grate (tests 11 to 32, inclusive), inches	60
Width of grate, inches	45½
Grate area (tests 2 to 10, inclusive), square feet	22
Grate area (tests 11 to 32, inclusive), square feet	19
Area of heating surface, square feet	375
Ratio of heating surface to grate area (tests 2 to 10)	16. 9
Ratio of heating surface to grate area (tests 11 to 32)	20. 0
Steam rating, square feet of radiation	10, 900
Steam rating, 1,000 B. t. u. per hour	2, 640
Air openings in grate, inches	2 11/16 by ½
Air openings, per cent of total area	48
Height from grate to furnace roof, at center, inches	24
Total number of sections (11 full size and 1 half size)	11½
Length of foundation, inches	113
Length of boiler, inches	115
Width of foundation, inches	54
Width of boiler, inches	53½
Height of boiler, inches	72½
Height of water line, inches	61
Height of ash pit, inches	16
Length of grate bars, inches	43½
Distance between centers of grate bars, inches	10
Distance from floor to smoke-pipe opening, inches	54
Diameter of smoke opening, inches	20
Area of smoke-pipe opening, square feet	2. 2
Area of openings—furnace to mixing chamber, square feet	1. 7
Area of openings in wing wall (tests 2–10, 26, and 32), square feet	2. 4
Area of openings checker wall, square feet	2. 7
Area of openings first pass, square feet	2. 0
Area of openings second pass, square feet	1. 5
Volume of combustion space total, cubic feet:	
For tests 2–10, with 70-inch grate and wing wall	51
For tests 11, 27, 28, 29, and 31, with short furnace and no wing wall	63
For tests 13, 14, 15, 16, 21, 22, 23, 25, 26, and 32	59
Length of flues, inches	97
Insulation, a 1-inch dead-air space surrounded by metal lath on which were mounted 1-inch 85 per cent magnesia blocks covered with thin coat of plastic cement. Total thickness of covering, inches	2

43064°—25†——2

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A steam jet was used in the smoke flue to produce induced draft for the high ratings.

The boiler was set up under the personal supervision of the company's representative.

CHANGES MADE IN BOILER AND FURNACE DURING THE TESTS

Changes in the arrangement of boiler sections affecting the grate area and combustion space were made as shown in Table 1. Tests 2 to 10 were made with six intermediate sections, each 10 inches wide, and an additional thin section 5 inches wide, over the grate and between the front and bridge-wall sections, set to meet demands for an extra large fuel capacity. Tests 11 to 32 were made with only five sections, each 10 inches wide, over the grate and between the front and bridge-wall sections, conforming to the original design of the boiler, and giving a larger combustion space back of the bridge wall. Mixing devices of various structures of brick were set in the combustion chamber to determine their relative advantages, if any, over a combustion chamber having no wing wall or checkerwork.

For tests 2 to 10, inclusive, a wing wall with a vertical slot 11 inches wide and 31 inches high was built in the combustion chamber, as shown in Figures 1, 2, and 3. All walls were removed from the combustion chamber when tests 11, 27, 28, 29, and 31 were run.

A mixing wall of brick laid up as checkerwork, with 24 openings, each 6½ by 2½ inches, was used for tests 13 to 25, inclusive. A wing wall having a vertical slot 14½ inches wide by 23½ inches high was used in test 32 to determine the effect of this slot in the mixing of the furnace gases.

TABLE 1.—*Changes made in boiler during the tests*

Test No.	Length of grate, inches	Arrangement and number of sections					Brickwork in combustion chamber	Ratio heating surface to—		Ratio combustion space grate surface
		Front	Over grate	Bridge wall	Combustion chamber	Back		Grate surface	Combustion space	
2–10	70	1	6½	1	2	1	Slot, wing wall	17	7.4	2.3
11	60	1	5	1	3½	1	No wall	20	6.0	3.4
13–25	60	1	5	1	3½	1	Checkerwork	20	6.4	3.2
26	60	1	5	1	3½	1	Slot, wing wall	20	6.4	3.2
27–31	60	1	5	1	3½	1	No wall	20	6.0	3.4
32	60	1	5	1	3½	1	Slot, wing wall	20	6.4	3.2

ADMISSION OF AIR OVER FUEL BED

After a preliminary test, provision for special means of admitting air over the fuel bed through the fire door was deemed advisable. To admit more air over the fuel bed an extra opening, 4¾ by 13

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inches, was cut in each fire door, directly below the regular air ports, and a shutter was provided to close the opening when desired. By means of this additional opening it was possible to supply the large

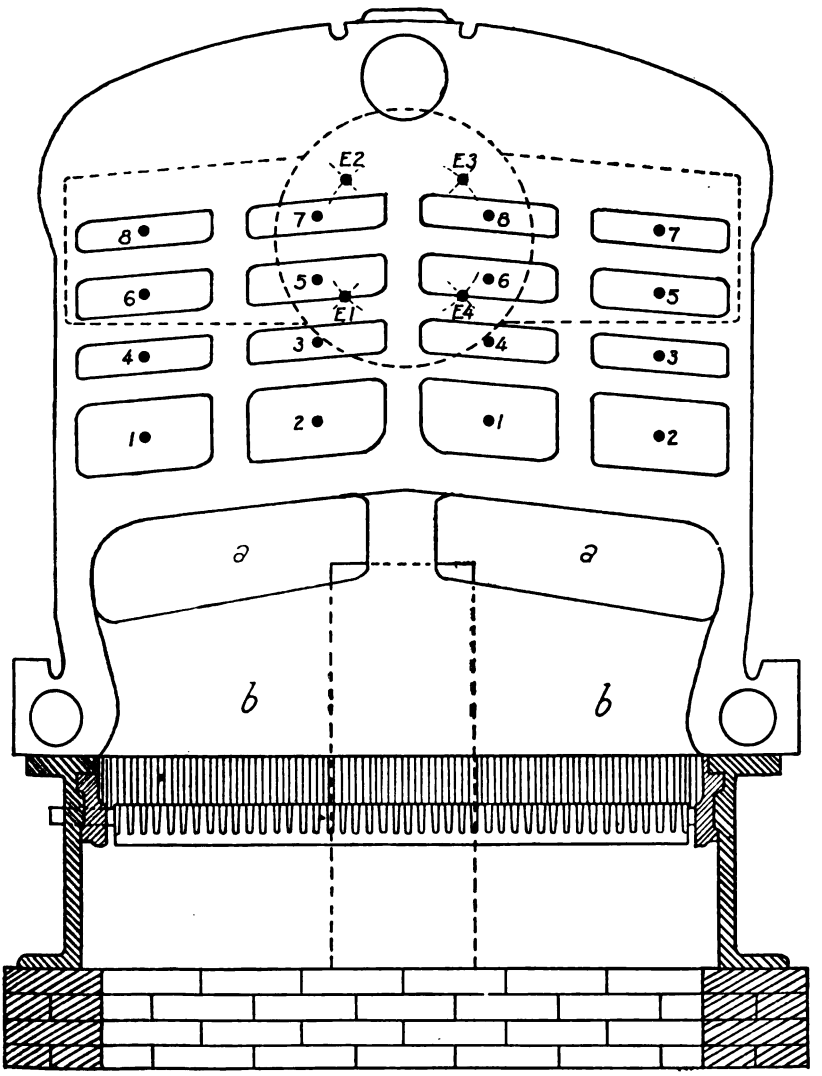

FIGURE 1.—Vertical cross section through the furnace: *a*. Openings in bridge-wall section to mixing chamber; *b*. wing walls, opening 11 inches wide and 31 inches high. Figures indicate tubes in which thermocouples were placed

quantities of air needed immediately after firing while the volatile matter was being rapidly distilled off, and then to shut off the air supply when not needed. Such manipulation is necessary.

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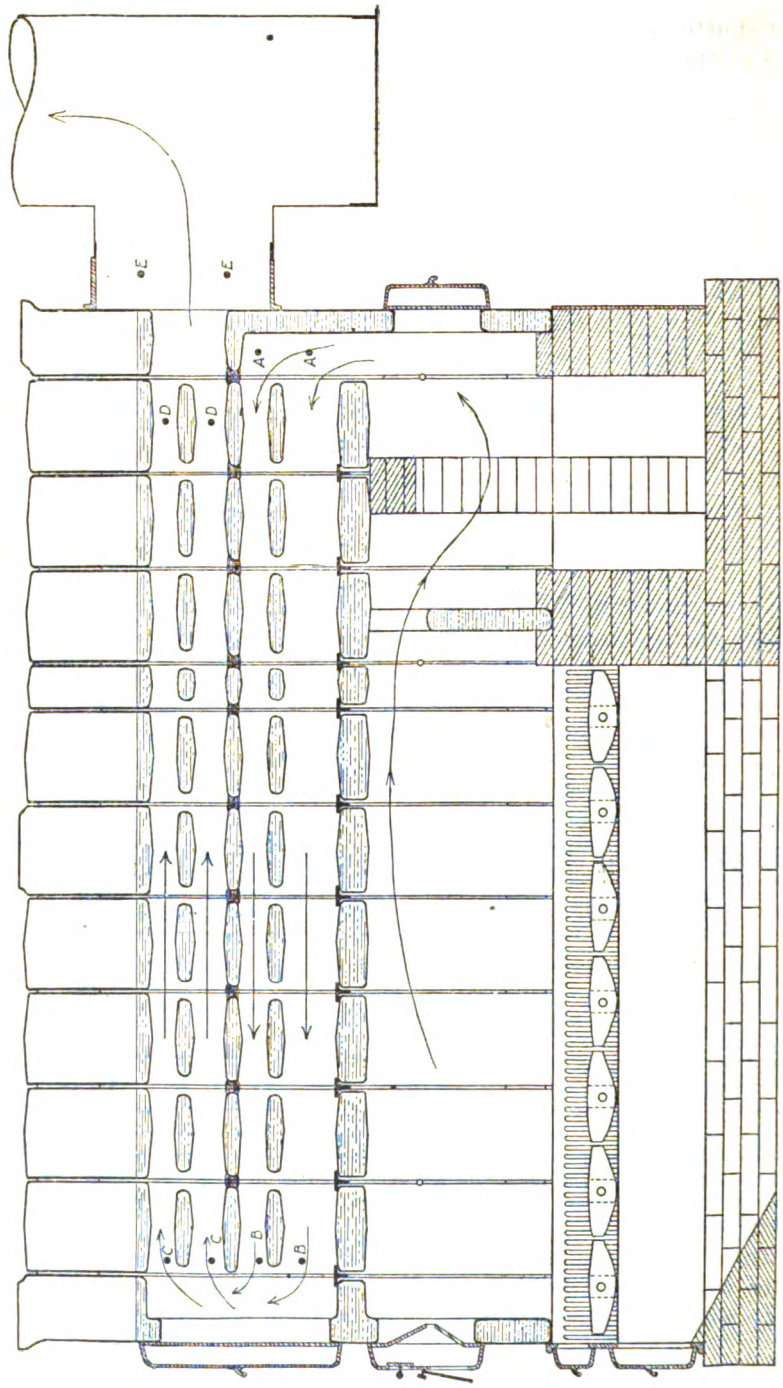

FIGURE 2.—Longitudinal vertical section through boiler, showing long shaking grate, combustion chamber, and flues as used in tests 2 to 10, inclusive. Letters show position of thermocouples

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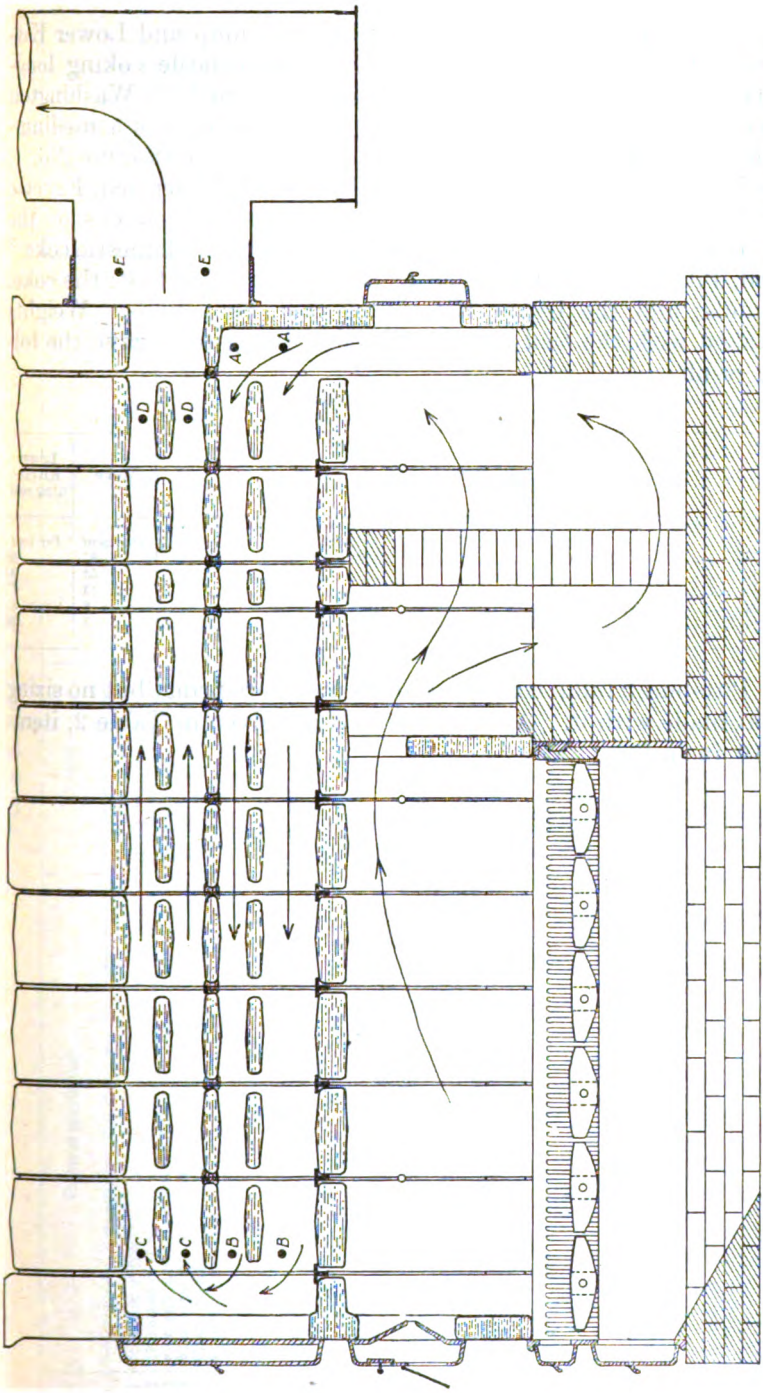

FIGURE 3.—Longitudinal vertical section through boiler, showing short shaking grate, combustion chamber, and flues as used in tests 11 to 32, inclusive. Letters show position of thermocouples

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FUEL BURNED

The bituminous coals used were Pittsburgh lump and Lower Kittanning run of mine; the former was a high-volatile coking long-flaming coal from the Rich Hill mine, Pittsburgh bed, Washington County, Pa., in the Pan Handle district; the latter was a medium-volatile noncoking medium-flaming coal from Melcroft mine No. 1, Lower Kittanning bed, also known as the "B" or Miller bed, Fayette County, Pa. The coke came from the by-product ovens of the Carnegie Steel Co., at Clairton, Pa., and is known as "domestic coke." As fired, Pittsburgh coal weighed 48 pounds per cubic foot; the coke, 33 pounds; and the Lower Kittanning coal, 50 pounds. Weights were taken with the coal loosely packed. Sizing tests gave the following result:

Sizing tests of fines

Screen (inch)	Coke	Lower Kittanning coal
	Per cent	*Per cent*
Through 1½	97	96
Through 1	53	90
Through ½	13	77
Through ¼	6	55
Through ⅛	3	39

The Pittsburgh lump coal was broken up before firing, but no sizing test was made with it. Analyses of fuels are given in Table 2, items 7 to 19 inclusive.

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TABLE 2.—*Results of tests*

Item No.	General particulars	Units	Pittsburgh lump coal						Clairton coke			
1	Number of trial		3	2	21	22	25	23	29	27	28	31
2	Duration of trial	Hours	24.3	19.1	42.9	28.4	20.0	14.0	40.3	25.0	16.6	13.3
3	Average interval between firing	Minutes	30	32	64	43	30	21	59	39	29	20
4	Fuel capacity of furnace	Pounds	1,650	1,650	1,410	1,410	1,410	1,410	970	970	970	970
5	Grate surface	Square feet	22.0	22.0	18.9	18.9	18.9	18.9	18.9	18.9	18.9	18.9
6	Fuel fired per hour	Pounds	247	314	140	211	300	429	155	240	329	450
	FUEL											
	Ultimate analysis as fired											
7	Hydrogen	Per cent	5.5	5.4	5.3	5.3	5.4	5.5	1.1	0.9	0.9	0.7
8	Carbon	do	75.8	76.9	74.1	73.5	75.4	75.9	79.3	80.7	80.7	78.9
9	Nitrogen	do	1.5	1.5	1.6	1.5	1.5	1.5	1.1	1.2	1.2	1.2
10	Oxygen	do	8.8	8.0	9.1	8.8	8.7	8.8	3.2	2.0	2.0	0.7
11	Sulphur	do	1.6	1.6	2.3	2.1	1.9	1.7	1.0	0.9	0.9	0.9
12	Ash	do	6.8	6.6	7.6	8.8	7.1	6.6	14.3	14.3	14.3	17.6
	Proximate analysis as fired											
13	Moisture	Per cent	2.4	1.4	2.4	2.6	2.4	2.5	3.6	2.3	2.3	0.8
14	Volatile matter	do	37.7	37.6	39.6	37.0	39.8	39.0	2.1	2.3	2.3	1.1
15	Fixed carbon	do	53.1	54.4	50.4	51.6	50.7	51.9	80.0	81.1	81.1	80.5
16	Ash	do	6.8	6.6	7.6	8.8	7.1	6.6	14.3	14.3	14.3	17.6
17	Fuel ratio, F. C.÷V. M.		1.41	1.45	1.27	1.39	1.27	1.33	38.10	35.26	35.26	73.18
	Calorific value of fuel per pound											
18	As fired	B. t. u	13,650	13,750	13,410	13,120	13,450	13,590	11,770	11,890	11,890	11,720
19	Moisture and ash free	do	15,040	14,940	14,890	14,800	14,860	14,950	14,330	14,260	14,260	14,370
20	Total fuel fired during test	Pounds	6,000	6,000	6,000	6,000	6,000	6,000	6,250	6,000	5,450	6,000
	ASH AND REFUSE											
21	Total ash and refuse removed	Pounds	537	593	480	565	397	388	1,112	1,155	1,032	1,027
22	Carbonaceous matter in ash and refuse	Per cent	26.7	35.3	23.0	12.0	10.6	19.3	18.0	18.4	18.4	21.3
23	Ash and refuse removed, per cent of fuel fired	do	9.0	9.9	8.0	9.4	6.6	6.5	17.8	19.3	18.9	17.1
	DRAFTS											
24	In ash pit	In. water	0.008	0.014	0.006	0.008	0.015	0.013	0.002	0.008	0.015	0.026
25	In furnace (front)	do	.07	.13	.02	.07	.13	.18	.04	.08	.14	
26	In furnace (rear)	do	.08	.14	.03	.08	.16	.22	.05	.09	.17	.28
27	In mixing chamber	do			.03	.10	.20	.30				
28	In combustion chamber	do	.24	.56	.06	.17	.31	.50	.07	.17	.29	.48
29	In stack	do	.53	.80	.18	.37	.62	1.29	.14	.37	.69	1.33

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TABLE 2.—*Results of tests*—Continued

Item No.	General particulars	Units	Pittsburgh lump coal						Clairton coke			
	AIR											
30	Temperature of air entering ash pit	Deg. F	79	83	72	79	78	76	79	82	82	86
31	Excess air in flue gas	Per cent	62	74	52	75	65	63	84	110	93	77
	FLUE GASES											
	Analysis of dry flue gas by volume											
32	Carbon dioxide	Per cent	11.0	10.3	11.6	10.3	10.5	10.9	11.1	9.7	10.6	11.5
33	Oxygen	do	8.2	9.1	7.3	9.1	8.4	8.2	9.6	11.0	10.1	9.1
34	Carbon monoxide	do	0.2	0.1	0.4	0.2	0.4	0.4	0.0	0.0	0.1	0.0
35	Nitrogen	do	80.6	80.5	80.7	80.4	80.7	80.5	79.3	79.3	79.2	79.4
36	Mean temperature of flue gases leaving boiler	Deg. F	682	632	512	694	758	832	426	532	673	757
	STEAM AND FEED WATER											
37	Gauge pressure of boiler	Pounds per square inch	6.4	5.5	2.7	5.0	4.3	6.0	2.5	3.5	1.7	3.2
38	Quality of steam leaving boiler	Per cent	99.6	99.2	99.7	99.1	98.8	98.6	99.8	99.8	98.2	99.6
39	Temperature of feed water	Deg. F	79	78	58	62	64	63	78	77	77	75
	RATES											
40	Per cent of builder's rating developed	Per cent	86	122	47	70	99	139	51	73	96	127
41	Heat transferred to water per hour	1,000 B. t. u	2,338	3,203	1,289	1,906	2,704	3,793	1,401	1,983	2,613	3,463
42	Heat transferred to water per square foot of heating surface per hour.	B. t. u	6,234	8,541	3,437	5,081	7,212	10,114	3,737	5,287	6,967	9,234
43	Fuel fired per square foot of grate surface per hour	Pounds	11.2	14.3	7.4	11.2	15.9	22.7	8.3	12.7	17.4	23.9
44	Fuel fired per cubic foot of combustion space per hour	do	4.8	6.2	2.4	3.6	5.1	7.3	2.5	3.8	5.2	7.1
	HEAT BALANCE (PER POUND OF FUEL AS FIRED)											
45	Heat transferred to water	B. t. u	9,480	10,185	9,211	9,026	9,015	8,850	9,025	8,261	7,949	7,693
46	Heat carried away by steam in flue gas	do	659	633	599	637	665	696	120	102	107	86
47	Heat carried away by dry flue gases	do	2,378	2,326	1,598	2,544	2,797	3,004	1,448	2,147	2,568	2,652
48	Heat lost by not burning CO	do	133	72	244	140	278	268	0	0	73	0
49	Heat lost by carbon in ash pit	do	348	506	268	164	102	182	465	515	506	530
50	Undetermined losses	do	652	28	1,490	609	593	590	712	865	697	759
51	Total and calorific value of fuel	do	1[2] 650	13,750	13,410	13,120	13,450	13,590	11,770	11,890	11,890	11,720

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	HEAT BALANCE (PER CENT OF HEAT IN FUEL AS FIRED)											
52	Heat transferred to water (therm. eff.)	Per cent	69.5	74.1	68.7	68.8	67.0	65.1	76.7	69.5	66.8	65.7
53	Heat carried away by steam in flue gas	do	4.8	4.6	4.5	4.9	4.9	5.1	1.0	0.9	0.9	0.7
54	Heat carried away by dry flue gases	do	17.4	16.9	11.9	19.4	20.8	22.1	12.3	18.1	21.6	22.6
55	Heat lost by not burning CO	do	1.0	0.5	1.8	1.1	2.1	2.0	0.0	0.0	0.6	0.0
56	Heat lost by carbon in ash pit	do	2.5	3.7	2.0	1.2	0.8	1.3	4.0	4.3	4.3	4.5
57	Undetermined losses	do	4.8	0.2	11.1	4.6	4.4	4.4	6.0	7.2	5.8	6.5
58	Total	do	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Gas-mixing device		Wing wall.			Checkerwork.				No brickwork.		

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TABLE 2.—*Results of tests*—Continued

Item No.	General particulars	Units	Lower Kittanning coal											
1	Number of trial		7	26	6	5	32	4	8	16	15	14	13	11
2	Duration of trial	Hours	37.6	26.0	25.8	24.6	19.8	20.1	7.7	40.0	26.8	26.7	6.1	17.8
3	Average interval between firing	Minutes	59	40	40	40	30	31	14	60	41	40	26	27
4	Fuel capacity of furnace	Pounds	1,720	1,470	1,720	1,720	1,470	1,720	1,720	1,470	1,470	1,470	1,470	1,470
5	Grate surface	Square feet	22.0	18.9	22.0	22.0	18.9	22.0	22.0	18.9	18.9	18.9	18.9	18.9
6	Fuel fired per hour	Pounds	160	231	235	244	304	299	352	150	224	229	343	337
	FUEL													
	Ultimate analysis as fired													
7	Hydrogen	Per cent	4.7	4.8	4.9	4.9	4.9	4.9	4.9	4.7	5.0	4.7	4.6	4.8
8	Carbon	do	75.9	75.5	76.8	76.3	77.3	76.0	76.5	73.7	74.3	76.2	74.6	77.2
9	Nitrogen	do	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
10	Oxygen	do	4.0	4.6	4.4	5.1	4.3	4.7	5.1	4.8	6.5	4.0	4.1	4.4
11	Sulphur	do	2.9	2.3	2.2	2.2	2.0	2.5	0.9	2.6	2.2	2.8	2.7	2.5
12	Ash	do	11.3	11.6	10.5	10.3	10.3	10.7	11.4	13.0	10.8	11.1	12.8	9.9
	Proximate analysis as fired													
13	Moisture	Per cent	1.6	2.2	2.0	2.8	1.9	2.4	2.7	2.5	4.5	1.6	1.7	2.0
14	Volatile matter	do	23.8	24.3	24.6	24.5	24.1	23.8	24.1	24.1	22.9	24.9	25.1	24.1
15	Fixed carbon	do	63.3	61.9	62.9	62.4	63.7	63.1	61.8	60.4	61.8	62.4	60.4	64.0
16	Ash	do	11.3	11.6	10.5	10.3	10.3	10.7	11.4	13.0	10.8	11.1	12.8	9.9
17	Fuel ratio, F. C.÷V. M.		2.66	2.55	2.56	2.55	2.64	2.65	2.56	2.51	2.70	2.51	2.41	2.66
	Calorific value of fuel per pound													
18	As fired	B. t. u	13,310	13,190	13,510	13,370	13,480	13,420	13,270	12,970	12,990	13,280	13,190	13,570
19	Moisture and ash free	do	15,280	15,310	15,450	15,380	15,360	15,430	15,440	15,340	15,340	15,210	15,420	15,410
20	Total fuel fired during test	Pounds	6,000	6,000	6,050	6,000	6,000	6,000	2,700	6,000	6,000	6,100	2,100	6,000
	ASH AND REFUSE													
21	Total ash and refuse removed	Pounds	658	787	662	761	776	750	197	761	730	690	155	595
22	Carbonaceous matter in ash and refuse	Per cent	18.8	24.4	24.8	24.5	30.2	32.2	28.5	27.0	31.9	20.2	25.2	19.0
23	Ash and refuse removed, per cent of fuel fired	do	11.0	13.1	10.9	12.7	12.9	12.5	7.3	12.7	12.2	11.3	7.4	9.9
	DRAFTS													
24	In ash pits	In. water	0.008	0.016	0.019	0.021	0.020	0.029	0.025	0.004	0.012	0.026	0.027	0.021
25	In furnace (front)	do	.08	.22	.24	.23	------	.25	.24	.08	.17	.19	.36	.34
26	In furnace (rear)	do	.10	.23	.25	.26	.23	.29	.27	.09	.18	.21	.39	.41
27	In mixing chamber	do	------	.28	------	------	.31	------	------	------	------	------	------	------
28	In combustion chamber	do	.17	.40	.38	.43	.52	.64	.55	.15	.36	.40	.67	.60
29	In stack	do	.31	.89	.78	.80	1.07	.90	1.24	.30	.74	.77	1.43	1.41

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	AIR												
30	Temperature of air entering ash pit	Deg. F	83	89	85	77	83	72	82	75	70	74	70	76
31	Excess air in flue gas	Per cent	88	193	117	129	160	101	101	136	154	142	81	101
	FLUE GASES													
	Analysis of dry flue gas by volume													
32	Carbon dioxide	Per cent	9.7	6.2	8.3	7.9	7.0	9.1	8.9	7.7	7.0	7.6	9.9	9.1
33	Oxygen	do	10.0	13.9	11.5	12.0	13.0	10.7	10.7	12.2	12.9	12.4	9.6	10.7
34	Carbon monoxide	do	0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.0	0.0
35	Nitrogen	do	80.2	79.9	80.2	80.1	80.0	80.1	80.3	80.1	80.1	79.9	80.5	80.2
36	Mean temperature of flue gases leaving boiler	Deg. F	530	526	559	557	592	587	615	496	507	525	601	621
	STEAM AND FEED WATER													
37	Gauge pressure of boiler	Pounds per square inch.	10.4	4.2	8.0	6.6	5.7	7.4	6.2	6.5	3.0	5.2	5.6	3.0
38	Quality of steam leaving boiler	Per cent	99.8	99.7	99.8	99.8	99.4	99.8	99.3	99.7	99.2	99.4	99.7	99.0
39	Temperature of feed water	Deg. F	78	77	78	77	72	77	74	48	43	43	49	47
	RATES													
40	Per cent of builder's rating developed	Per cent	57	76	83	84	99	102	117	51	73	80	120	115
41	Heat transferred to water per hour	1,000 B. t. u	1,550	2,071	2,273	2,302	2,693	2,767	3,188	1,391	1,989	2,172	3,270	3,122
42	Heat transferred to water per square foot of heating surface per hour.	B. t. u	4,135	5,522	6,061	6,138	7,181	7,378	8,500	3,710	5,304	5,792	8,721	8,324
43	Fuel fired per square foot of grate surface per hour.	Pounds	7.3	12.2	10.7	11.1	16.1	13.6	16.0	8.0	11.9	12.1	18.2	17.8
44	Fuel fired per cubic foot of combustion space per hour.	do	3.1	3.9	4.6	4.8	5.2	5.9	6.9	2.5	3.8	3.9	5.8	5.3
	HEAT BALANCE (PER POUND OF FUEL AS FIRED)													
45	Heat transferred to water	B. t. u	9,711	8,973	9,676	9,429	8,864	9,259	9,043	9,274	8,868	9,495	9,531	9,166
46	Heat carried away by steam in flue gas	do	530	538	558	561	566	570	571	527	565	533	538	563
47	Heat carried away by dry flue gases	do	2,016	3,011	2,520	2,646	3,164	2,442	2,631	2,284	2,607	2,573	2,339	2,696
48	Heat lost by not burning CO	do	76	0	0	0	0	40	84	0	0	97	0	0
49	Heat lost by carbon in ash pit	do	305	465	393	451	568	586	305	497	564	332	270	276
50	Undetermined losses	do	672	203	363	283	318	523	636	388	386	250	512	869
51	Total and calorific value of fuel	do	13,310	13,190	13,510	13,370	13,480	13,420	13,270	12,970	12,990	13,280	13,190	13,570
	HEAT BALANCE (PER CENT OF HEAT IN FUEL AS FIRED)													
52	Heat transferred to water (therm. eff.)	Per cent	73.0	68.0	71.6	70.5	65.8	69.0	68.1	71.5	68.3	71.5	72.3	67.5
53	Heat carried away by steam in flue gas	do	4.0	4.1	4.1	4.2	4.2	4.2	4.3	4.1	4.3	4.0	4.1	4.1
54	Heat carried away by dry flue gases	do	15.1	22.8	18.7	19.8	23.5	18.2	19.8	17.6	20.1	19.4	17.7	19.9
55	Heat lost by not burning CO	do	0.6	0.0	0.0	0.0	0.0	0.3	0.6	0.0	0.0	0.7	0.0	0.0
56	Heat lost by carbon in ash pit	do	2.3	3.5	2.9	3.4	4.2	4.4	2.3	3.8	4.3	2.5	2.0	2.0
57	Undetermined losses	do	5.0	1.6	2.7	2.1	2.3	3.9	4.9	3.0	3.0	1.9	3.9	6.5
58	Total	do	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Gas-mixing device					Wing wall.				Checkerwork.				No brick work.

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DISCUSSION OF RESULTS OF TESTS

FUELS USED AND MIXING STRUCTURES EMPLOYED

Table 2 shows the main results obtained. The tests are grouped according to fuel used and separated according to the mixing structures of wing walls or checker-type brickwork employed between the mixing and combustion chambers. The tests having similar fuel and furnace details are grouped from left to right so that the low ratings come first, and is followed by those at higher ratings. Six tests were run with Pittsburgh coal—tests 2 and 3, with wing walls; and tests 21, 22, 23, and 25, with a checkerwork fire-brick wall. Four tests were made with coke in which no brickwork was used for mixing the gases. Twelve tests were made with Lower Kittanning coal—tests 7, 26, 6, 5, 32, 4, and 8, with a wing wall; tests 16, 15, 14, and 13, with checkerwork wall; and test 11 with no brickwork in the combustion chamber.

PURPOSE OF DIFFERENT TESTS

Test 1 was a preliminary run, of short duration, to familiarize the observers with the technique developed for the series.

Test 9 was made, at the suggestion of the manufacturer, to obtain data on a firing period with an extremely heavy firing of 1,300 pounds of Lower Kittanning coal. Immediately after firing, the flue-gas temperature was low but increased as the fuel ignited. The fuel packed closely and ignited slowly; it burned in channels or holes to the outer edge of the fuel bed, and frequent raking and loosening of the fuel was necessary to continue combustion at a high rate. The stack draft carried the larger part of the time was 1.5 inches of water, which was nearly equaled during later regular tests at high ratings. While the boiler was being operated at the extremely high capacity developed at the end of the fourth hour, the rear-section casting cracked and the run had to be stopped at once.

In test 10 at 125 per cent rating or more for 15 hours, a water leak developed and the test was discontinued. Results were not computed.

Test 24 was a special furnace test with Lower Kittanning coal. The fuel bed was built up to 6 or 8 inches, then a charge of 935 pounds of fresh coal was fired; readings of drafts and stack temperatures were taken, and flue-gas analyses were made for about five hours. Draft readings averaged 1.1 inches at stack, 0.7 inch in combustion chamber, and 0.4 inch at furnace front. The stack temperature was about 300° F. for the first hour and 650° F. for the last hour, averaging about 500° F. for the whole period. The average flue-gas analysis for the full period, per cent by volume, was CO_2, 6.0; O_2, 14.3. For the first hour the per cent CO_2 was 2.6, and O_2, 18.0; for the last hour the per cent CO_2 was 8.7, and

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O_2, 11.5. The actual water evaporated during each consecutive hour was 240, 1,465, 1,825, 1,910, and 2,600 pounds. Holes formed at the front of the fuel bed 2 feet from the firing door. Frequent attention by the fireman was necessary to cover the holes and to loosen up the packed fuel bed in an endeavor to get more rapid ignition.

Test 30 was a coke test in which 150 per cent rating was attempted; after 3 hours operation it was stopped because of a cracked front casting. Test 31 takes its place in Table 2.

During tests 4, 9, 10, 13, and 30, one or more of the sections developed defect or cracks in the castings. As these were quite small during tests 4 and 13, closing readings were taken and the results included in the report to represent ratings of 102 and 120 per cent, respectively, with Lower Kittanning coal. The boiler was operated at 139 per cent rating over 14 hours during test 23, and at over 100 per cent during many tests, without any apparent defects developing in the castings. Hence it is difficult to ascribe the several failures of castings entirely to the effect of high rates of operation. Unrelieved stresses within the cast iron in the sections augmented by stresses due to localized high temperatures may have been the direct cause.

A larger cast-iron boiler used for the tests reported in Technical Paper 303 [2] was rated on the basis of heat transfer of 4,640 B. t. u. per square foot of heating surface per hour for 100 per cent of builder's rating. An average rate of heat transfer of 5,440 B. t. u. per square foot per hour obtained for their test at 117 per cent of builder's rating was the highest rate reported for that series. The boiler used in the present series of tests was rated on a basis of heat transfer of 7,280 B. t. u. per square foot of heating surface per hour for 100 per cent of builder's rating. During test 23, made at 139 per cent of builder's rating, the average rate of heat transfer was 10,100 B. t. u. per square foot of heating surface per hour.

In no test did the castings develop defects when the boiler was operating below 100 per cent of builder's rating and it is understood that the manufacturer recommends this boiler only for loads not exceeding that rating. Tests of this boiler above 100 per cent rating therefore should be understood to have been made only for their general engineering interest, and for the purpose of establishing outside limitations for such boilers.

Test 12 was of short duration; it was run for smoke observations which are given later. Special test 17 was run with no air supplied over the fuel bed and was for comparison with test 18 in which air was supplied. Both tests were run at about 75 per cent rating. Special test 19 with an 8-inch fuel bed, and no air supplied over the fuel was run for comparison with test 20, which had an 11½-inch fuel bed and no air supply over it. In these four tests the front cleaning

[2] Blizard, John, Nell, James, and Houghten, F. C., Value of coke, anthracite, and bituminous coal for generating steam in a low-pressure cast-iron boiler: Tech. Paper 303, Bureau of Mines, 1922, p. 15.

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doors were sealed around the joints to minimize leakage of air. Table 6 gives the analyses of the gases for these special tests.

COMPARATIVE STEAMING VALUE OF FUELS

Owing to variations in the commercial value of fuel, and in boiler and furnace efficiency, it is not possible to obtain comparative figures that will always represent the steaming values of fuels. Since the steaming value is the efficiency multiplied by the calorific value of each fuel, the results obtained must be considered in connection with the conditions under which they were obtained. They do properly indicate what is possible under these conditions. Figure 4 shows the heat transferred to water, or the useful heat per pound of fuel for each fuel tested (Table 2, line 45) as ordinates plotted against the

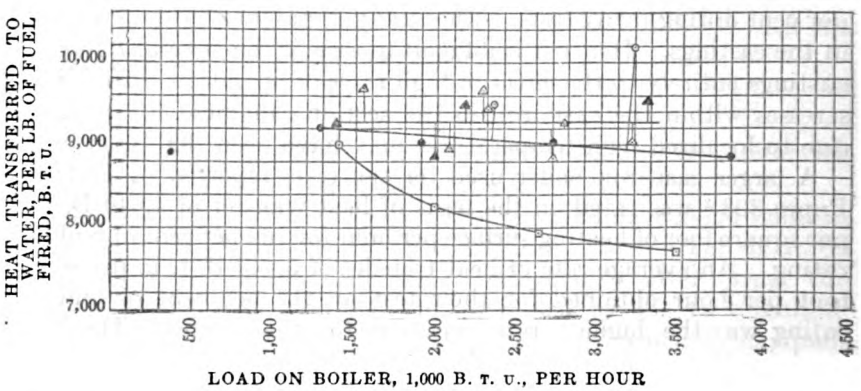

FIGURE 4.—Relative steaming value of fuels tested: △, Lower Kittanning coal, wing wall; ▲, Lower Kittanning coal, checkerwork; ⊙, Pittsburgh coal, wing wall; ●, Pittsburgh coal, checkerwork; ⊡, coke, no brickwork

load on the boiler in British thermal units transferred to water per hour. In most tests the Pittsburgh coal shows somewhat lower values for heat absorbed by water than does the Lower Kittanning coal. An exception was test 2, run with the boiler newly installed, its surfaces clean inside and out, and the air infiltration low because the joints between sections were tight. In this test, item 50 (undetermined losses), obtained by difference, is too low to account for radiation loss included therein which from the tests and by calculating the radiation, might be expected to be about 200 or 300 B. t. u. per pound of fuel fired. As the coke had a high content of ash, its steaming value at the rated capacity of the boiler was only about 90 per cent of that of equal weights of the bituminous coals used.

THERMAL EFFICIENCY

Table 2, line 52, gives the over-all thermal efficiency. Figure 5 shows by curves the over-all thermal efficiencies obtained with the

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three fuels at various rates of steaming. The high point to the right of the curve is for test 13, which was a short run with Lower Kittanning coal. The point is included because it represents the highest rating obtained with this coal. Pittsburgh coal showed the lowest efficiency at the low loads, but at medium and high loads the efficiency became higher than that of coke, and approached that of Lower Kittanning coal. Test 2, a complete run, had rather high efficiency and does not leave enough in the unaccounted-for item to provide for radiation; however, the test is included because it gives indication of the results obtainable with Pittsburgh coal at high loads. The series of tests with coke shows the highest efficiency obtained at low loads; at higher rates of operation the efficiencies dropped below those for both Pittsburgh and Lower Kittanning coals.

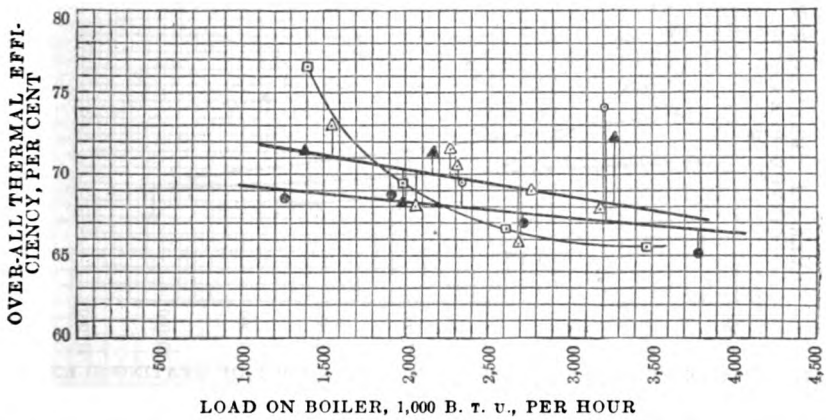

FIGURE 5.—Boiler, furnace, and grate thermal efficiencies at different rates of steaming, based on gross calorific value of fuel: △, Lower Kittanning coal, wing wall; ▲, Lower Kittanning coal, checkerwork; ⊙, Pittsburgh coal, wing wall; ●, Pittsburgh coal, checkerwork; ⊡, coke, no brickwork

RATE OF HEAT TRANSFER TO WATER PER SQUARE FOOT OF HEATING SURFACE PER HOUR

Figure 6 shows the thermal efficiencies with the three kinds of fuel when the average rate of heat transferred to water ranged from 3,000 to 10,000 B. t. u. per square foot of heating surface per hour, as given in line 42 of Table 2. Comparison of these values with the similar values for coke in a larger cast-iron boiler, as reported in Technical Paper 303,[3] shows that the efficiencies of boiler and furnace are nearly as high even though the average rate of heat transfer per square foot of heating surface is so much greater.

The reader should note that each square foot of fire-box heating surface received and transferred much more heat than the values

[3] Blizard, John, Neil, James, and Houghten, F. C., Value of coke, anthracite and bituminous coal for generating steam in low-pressure cast-iron boiler: Tech. Paper 303, Bureau of Mines, 1922, p. 13.

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given in item 42, Table 2, which are averages for all the heating surface. The drop in temperature along the path of the gases is shown by Figure 14, page 30, of this report.

HEAT BALANCE SHOWN BY CURVES

Figures 7, 8, and 9 give the results of tests with Pittsburgh coal, coke, and Lower Kittanning coal. At the top is shown the "undetermined losses" from Table 2, line 57, which includes radiation, convection, and other unaccounted-for losses.

The loss by carbonaceous matter in the ash is represented by the vertical distance between the top curve and the one just below it. Between this curve and the one underneath it are shown the total flue-gas losses which include, besides the dry-gas loss, the loss due

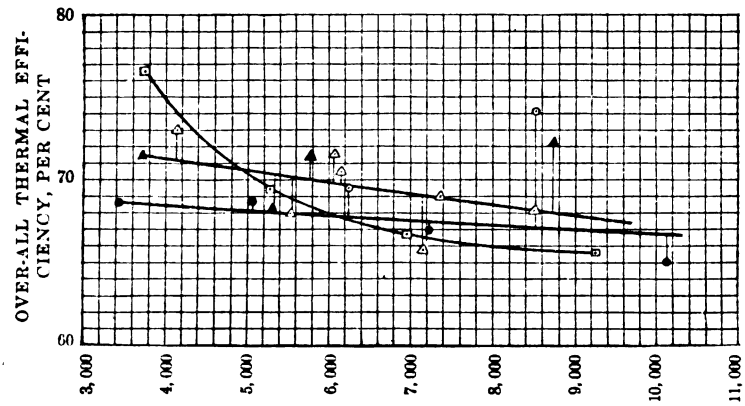

FIGURE 6.—Boiler, furnace, and grate thermal efficiencies at various rates of heat absorption per square foot of heating surface per hour in B. t. u. for the several fuels, based on gross calorific value of fuel: △, Lower Kittanning coal, wing wall; ▲, Lower Kittanning coal, checkerwork; ⊙, Pittsburgh coal, wing wall; , Pittsburgh coal, checkerwork; ⊡, coke, no brickwork

to steam from the moisture in the coal, the loss from the steam formed by the burning of the hydrogen in the fuel, and the loss from the carbon monoxide in the flue gas. At the bottom of each figure are three curves, which represent the sum of losses in flue gases, the combined carbon monoxide and steam loss, and, nearest the bottom, the carbon monoxide loss.

In the three figures the efficiency curves for both bituminous coals are somewhat irregular but do not vary much with increased loads; in the curves for coke the efficiency decreases as the load is increased. For a given fuel, the shape of the efficiency curve will vary with the furnace and grate design, the volume of combustion space per pound of fuel fired, and the correctness of the mixing of the air supply, as well as with the method of firing, and the available drafts and their manipulation.

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HEAT CARRIED AWAY BY STEAM IN FLUE GAS

Item 53 of Table 2 is the calculated value of heat carried away by the steam in the flue gases and shows a greater loss for Pittsburgh coal than for Lower Kittanning coal, while both coals show higher losses than for coke. These differences are for the greater part due

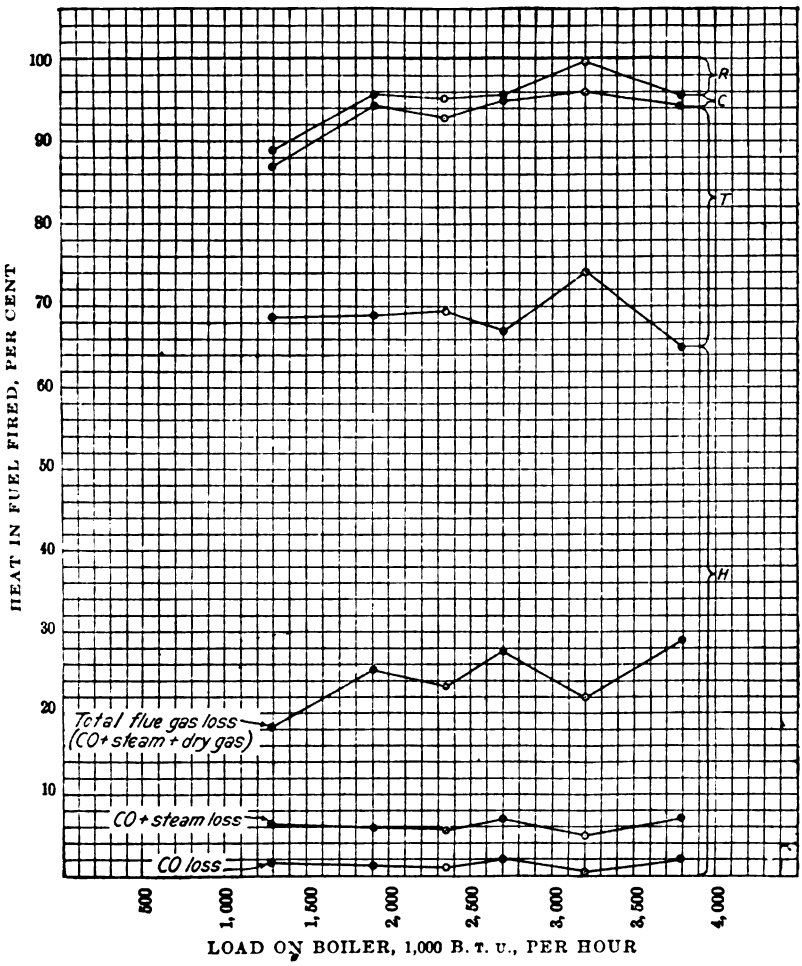

FIGURE 7.—Heat account of Pittsburgh coal at different rates of steaming: *R*, Radiation and unaccounted for; *C*, carbonaceous matter in ash; *T*, total heat content of flue gases; *H*, thermal efficiency; ⊙, with wing wall; ●, with checkerwork

to differences in the hydrogen content of the fuels, a point that should be considered in a comparison of the steaming value of fuels.

When a pound of fuel is completely burned, the hydrogen unites with 8 times its weight of oxygen to form water that weighs 9 times as much as the hydrogen. This must be heated from air temperature, *t*, to flue-gas temperature, *T*, so that the heat carried away in

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steam from 1 pound of coal amounts to 9 H (0.48 T+1,082−t), where H is the hydrogen per pound of fuel fired, and 0.48 T+1,082−t represents the total heat per pound of steam at about atmospheric pressure and at the temperature of the flue gas, above 1 pound of water at the temperature of entering air. The calorific value as

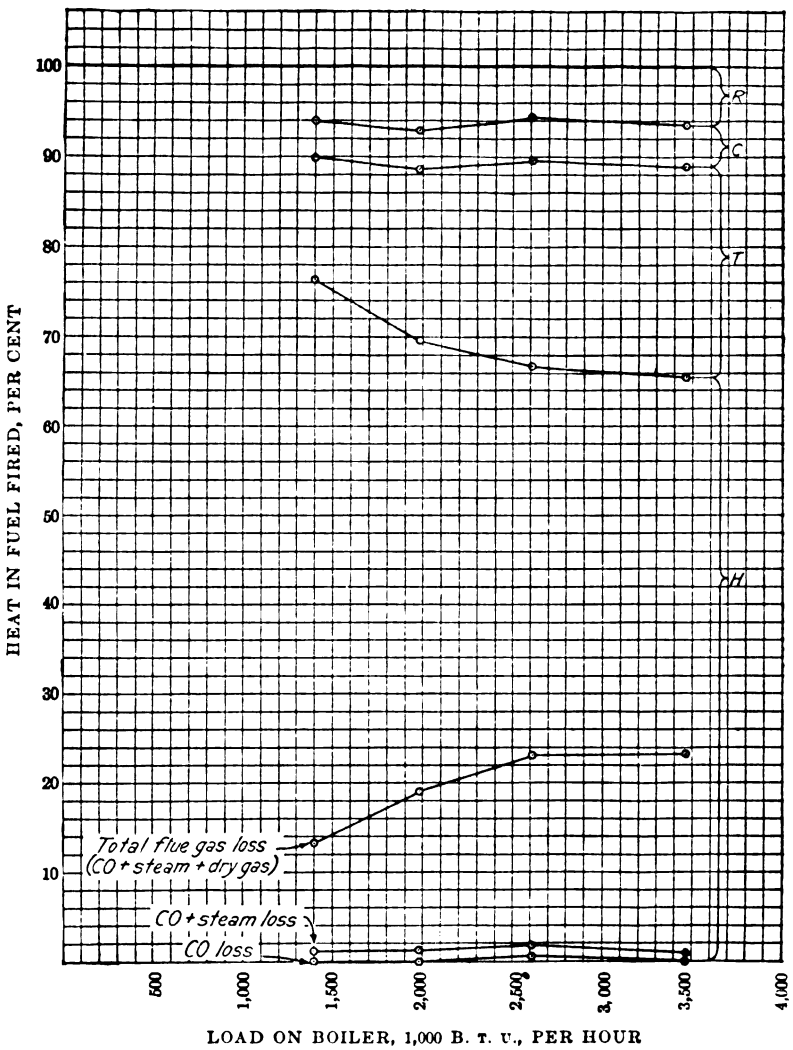

FIGURE 8.—Heat account of coke at different rates of steaming: *R*, Radiation and unaccounted for; *C*, carbonaceous matter in ash; *T*, total heat content of flue gases; *H*, thermal efficiency. No brickwork

usually reported and as given in the Table 2, items 18 and 19, is the gross heating value determined in the bomb calorimeter; it includes the heat given up by the products of combustion as they are brought back to the initial temperature, and by the condensation of steam formed from the fuel.

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To allow for the heat in steam in the flue gas from a boiler, which is not practicable to use by condensing, a net or low calorific value is sometimes calculated, and thermal efficiencies are obtained as the ratio of heat absorbed by steam raised in the boiler to the net calorific value of fuel. The net calorific value at 68° F. of a fuel in B. t. u.

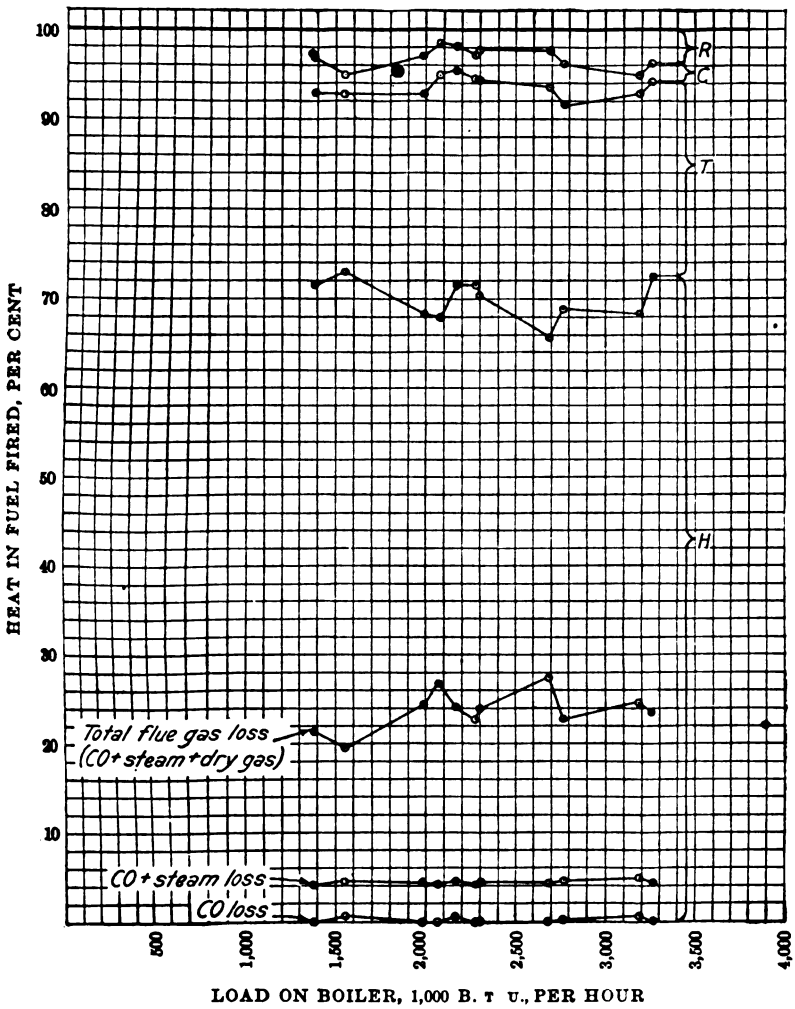

FIGURE 9.—Heat account of Lower Kittanning coal at different rates of steaming: *R*, Radiation and unaccounted for; *C*, carbonaceous matter in ash; *T*, total heat content of flue gases; *H*, thermal efficiency. ⊙, with wing wall; ●, with checkerwork

per pound is equal to the gross calorific value $-9 \times H \times 1{,}040$ B. t. u., where 1,040 B. t. u. is the value recommended by the American Society for Testing Materials as the latent heat of steam per pound under these conditions.

Table 3 shows the efficiencies of the boiler when based on the gross as well as the net calorific value of fuel for some of the tests.

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TABLE 3.—*Comparison of thermal efficiencies based on the gross and the net calorific values of the fuels—Pittsburgh coal, coke, and Lower Kittanning coal*

Fuel	Thermal efficiencies based on gross calorific values			Thermal efficiencies based on net calorific values		
	Pittsburgh coal	Coke	Lower Kittanning coal	Pittsburgh coal	Coke	Lower Kittanning coal
Thermal efficiency, per cent	68.7	76.7	73.0	71.3	77.4	75.5
Per cent of builder's rating	47	51	57	47	51	57
Thermal efficiency, per cent	68.8	69.5	68.0	71.5	70.0	70.4
Per cent of builder's rating	70	73	76	70	73	76
Thermal efficiency, per cent	67.0	66.8	69.0	69.6	67.3	71.4
Per cent of builder's rating	99	96	102	99	96	102
Thermal efficiency, per cent	65.1	65.7	68.1	67.7	66.0	70.6
Per cent of builder's rating	139	127	117	139	127	117

Table 3 shows that the increase in efficiency of the bituminous coal tests, based on the net calorific value, is about 4 per cent of the efficiency based on the gross calorific value for Pittsburgh coal, 1 per cent for coke, and 3.5 per cent for Lower Kittanning coal.

LOSS THROUGH COMBUSTIBLE IN ASH

The loss of combustible matter in ash varies with the ash content of the fuel, and the efficiency with which the fuel content is burned out in practice as indicated by the combustible content in the ash and refuse removed from the ash pit and grate. The size of fuel, physical properties of both coal and ash, fusibility, design and air openings of grates, and the firing and cleaning methods—all have an effect on the loss caused by combustible in ash. The Pittsburgh coal contains 7 to 9 per cent ash, the coke 14 to 18 per cent, and the Lower Kittanning coal 10 to 13 per cent. The heat loss (item 56 in Table 2) is from 1 to 4 per cent (average 2 per cent) for Pittsburgh coal, about 4 per cent for coke, and from 2 to 4 per cent (average 3 per cent) for Lower Kittanning coal.

All tests were made with the same shaking type of grate with air spaces ½-inch wide, and air openings in grate 48 per cent of the total area. The heat loss in refuse varied almost directly as the ash content of the fuels.

HEAT LOST UP STACK BY DRY FLUE GASES

The percentages of heat losses with the three fuels caused by the dry flue gases leaving the boiler are shown in Figure 10. The tests with coke show lower loss at low ratings and higher loss at high ratings than was found with the bituminous coals. A possible reason for this is that no mixing devices were used in the combustion chamber with the result that at the high ratings the gases continued burning through the pass and the gases left the boiler at high temperature.

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Tests 2 and 3 with Pittsburgh coal, shown by points below the line, were with a wing wall; hence it seems probable that when the gases were mixed more thoroughly, combustion was completed sooner and the gases had more time to give up heat to the boiler flue surfaces. This inference is supported by the temperature of the flue gases being lower than for a similar rating in test 23, which was made with checkerwork to mix the gases in the combustion chamber.

With Lower Kittanning coal, tests 15, 26, and 32 showed higher flue-gas losses than the other tests with this coal due to the high excess air. They also showed greater losses due to higher temperature of flue gas than the other tests. Tests 4 and 16 gave lower losses.

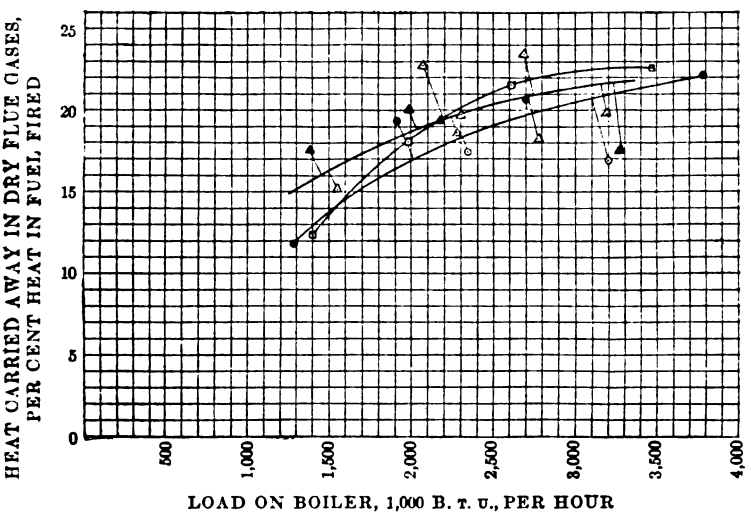

FIGURE 10.—Heat carried away by dry flue gases: △, Lower Kittanning coal, wing wall; ▲, Lower Kittanning coal, checkerwork; ○, Pittsburgh coal, wing wall; ●, Pittsburgh coal, checkerwork; ⊡, coke, no brickwork

than average because of lower excess air in gases and the lower temperature of gases leaving the boiler.

FLUE-GAS TEMPERATURE

Figure 11 shows the variation of flue-gas temperature with the fuels burned at different rates. The temperatures are higher for Pittsburgh coal than for coke or Lower Kittanning coal. The point representing test 2 falls below the line for all other tests at this rating, largely because of the facts that (1) the grate was longer for this test, therefore less coal was burned per square foot of grate and a lower temperature was measured as the gases left the combustion chamber; and that (2) the wing wall seemed to mix the gases better than the checkerwork, therefore combustion was completed earlier

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along the path of the gases. The point below the curve for Lower Kittanning coal is probably due to the same causes, as the same grate and wing wall were used.

The low flue-gas temperatures for Lower Kittanning coal in the medium-rate tests were largely due to the high excess air.

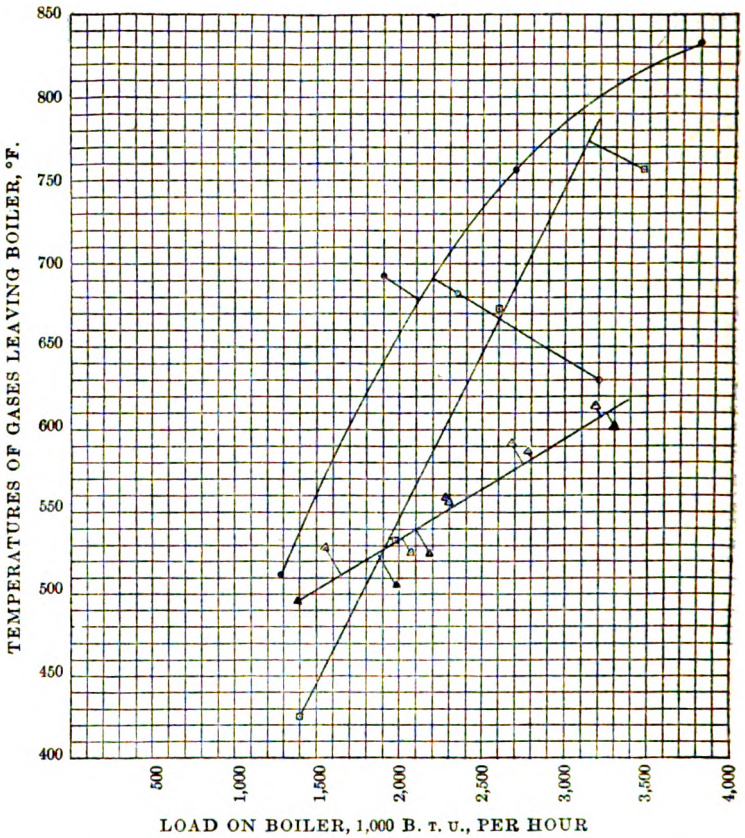

FIGURE 11.—Flue-gas temperatures at different rates of steaming with the several fuels: △, Lower Kittanning coal, wing wall; ▲, Lower Kittanning, checkerwork; ⊙, Pittsburgh coal, wing wall; , Pittsburgh coal, checkerwork; ⊡, coke, no brickwork

EXCESS AIR IN FLUE GASES

Figure 12 gives the excess air in the flue gases when the three fuels were burned at different rates. With Pittsburgh coal the excess air increased with the load, but with both coke and Lower Kittanning coal the excess air decreased with the load, so that at the highest loads all three fuels were burned with nearly the same excess of air. The points for Lower Kittanning coal are high mostly because of the higher resistance to air flowing through the fuel bed; this resistance increases the air leakage into the flues because a higher draft is carried when that coal is burned.

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EXCESS AIR, TEMPERATURE, AND FLUE-GAS LOSS

In order to show the relation, at similar rates of operation, between excess air with flue-gas temperature and flue-gas losses, the curves in Figure 13 were drawn for Lower Kittanning coal. If a straight line were drawn through the two points for 51 and 57 per cent ratings below the lower curve, it would show an increase in total flue-gas loss with increasing excess air. The two ratings, however, were not exactly the same.

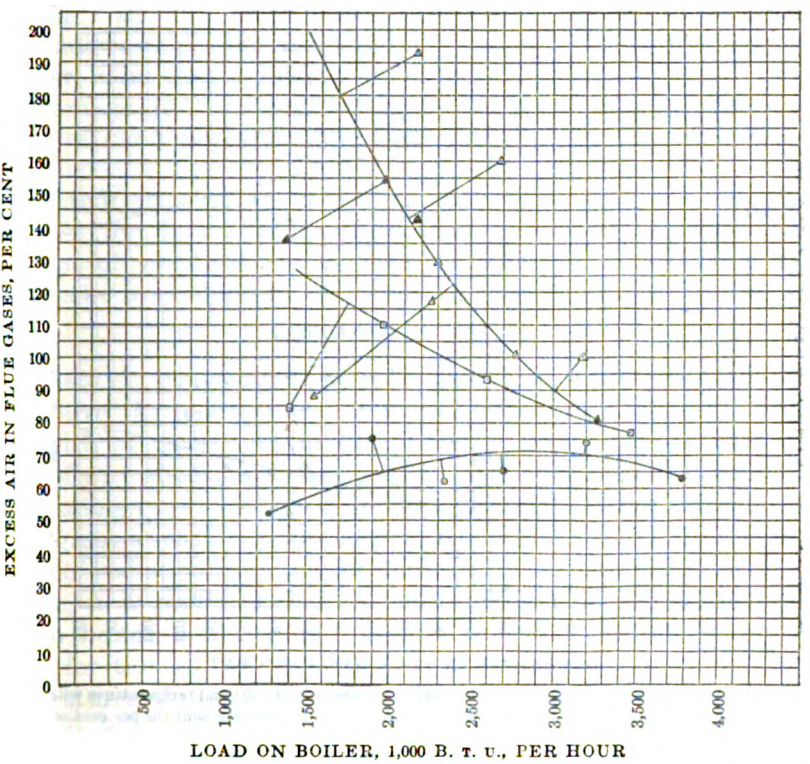

FIGURE 12.—Excess air in flue gases at different rates of steaming with the several fuels: △, Lower Kittanning coal, wing wall; ▲, Lower Kittanning coal, checkerwork; ⊙, Pittsburgh coal, wing wall; ●, Pittsburgh coal, checkerwork; ⊡, coke, no brickwork

The group of tests run at ratings of 73 to 84 per cent also show a decided increase in flue-gas loss with an increase in the excess air because of the increase in the mass of the flue gases, even though these gases were leaving at a somewhat lower temperature.

The three tests run at over 100 per cent of builder's rating also show an increase in flue-gas loss and a decrease of flue-gas temperature with increasing excess air. Between the ratings of 73 and 120 per cent of builder's rating the total flue-gas losses are lowest with about 100 per cent excess air when Lower Kittanning coal is burned in this

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furnace; but between 51 and 57 per cent of builder's rating it appears that less than 90 per cent excess air gave the best efficiency.

In all the tests with Lower Kittanning coal, enough air was supplied to burn the carbon monoxide, therefore the losses just considered are due almost entirely to heat carried away in dry flue gas, and in steam formed from the moisture in the coal and from the burning of hydrogen. In operation at high ratings it should be remembered that with this additional air more draft is required to move the gases through the boiler.

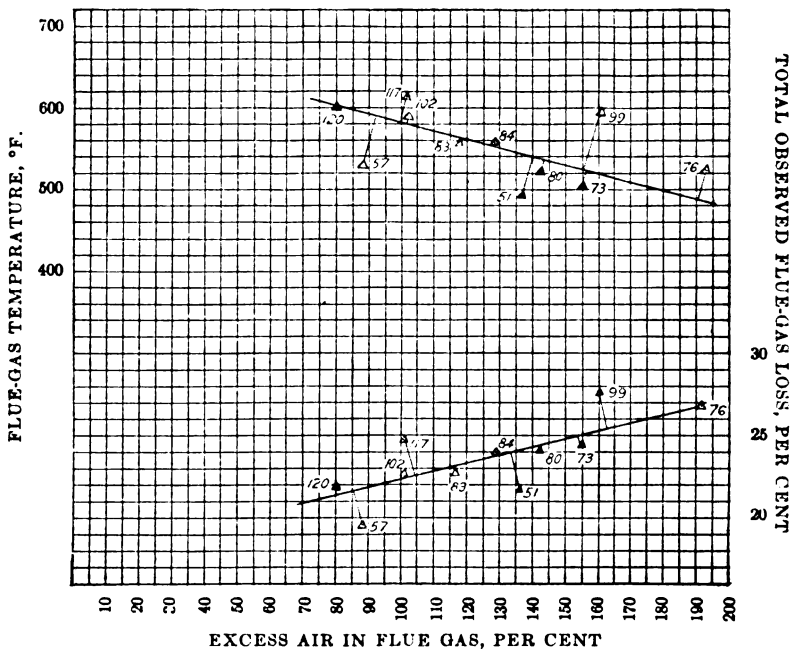

FIGURE 13.—Variations of the total flue-gas loss (dry gas, steam, and CO) and temperatures with varying air supply for several ratings with Lower Kittanning coal. Numbers represent the per cent of builder's rating developed; △, with wing wall; ▲, with checkerwork

MIXING DEVICES IN THE COMBUSTION CHAMBER

In order to obtain data on the effect of mixing devices in the combustion chamber, tests were made with wing walls and with checkerwork walls of fire brick. Wing walls, leaving a vertical slot 31 inches high and 11 inches wide on the center line of the boiler were built in the combustion chamber as shown in Figures 1 and 2 (pp. 7 and 8), and used in tests 2 to 10, inclusive, and in test 26. Test 32 was run in order to obtain comparative data on a wing wall with a slot 14½ inches wide and 23½ inches high. The checkerwork wall was built of fire brick and had 24 openings each approximately 2½ by 6½ inches. The total area of the openings in the checkerwork and the wing-wall slots was approximately the same.

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The tests with Pittsburgh coal were the only ones which showed much combustible in the stack gases. Tests 2 and 3 were run with the wing wall and tests 21, 22, 23, and 25, with the checkerwork. Table 2, items 31, 34, and 40, gives a general idea of the relative values of the wing wall and checkerwork as gas-mixing devices. Test 3 is comparable in rating with tests 22 and 25; likewise the excess air for these tests is about the same. However, test 3 shows less carbon monoxide in the stack gases than test 25. Similarly, in tests 2 and 23 the ratings and excess-air supply are comparable, but test 2 shows a much lower carbon monoxide content. These facts indicate that the wing-wall type is a better mixing device; however, more tests are needed to obtain conclusive evidence. The disadvantage of the wing wall seems to be its "torch effect" in concentrating high-temperature flame upon limited areas of the heating surface.

A further examination of the gas analyses in Table 2 shows that the gases from Lower Kittanning coal were mixed about as well with one type of mixing device as with the other. Both the wing wall and checkerwork stood up well under the test conditions.

TEMPERATURE IN FURNACE

In test 15, temperatures were measured in the furnace about 1 foot above the fuel bed and at points 1 foot apart from the firing door, with an exposed platinum and platinum-rhodium thermocouple made of wire about 22 B. & S. gauge. While the indicated temperature readings may be higher or lower than the actual temperature of the gases at each position, depending on the effect on the thermocouple of radiation from the hot flame or from the cooler walls of the furnace, it is probable that the measured temperatures are fairly close to the true temperature. Figure 14 shows the measured temperatures for test 15, which as plotted give the general trend of the temperatures of the gases passing through the furnace and boiler.

The broken part of the curve represents the average of the readings of the platinum and platinum-rhodium thermocouple for a few firing periods, and the solid part represents the average of the readings of the Hoskins and copper-constantan couples, which were permanently set in the gas passages and were read throughout the entire test.

TEMPERATURE OF GASES IN BOILER FLUES

In some of the tests, temperatures were measured along the path of the gases at each end in the boiler flues, as indicated in Figures 1, 2, and 3. Thermocouples of Hoskins wire, alumel and chromel "P" (22 B. & S. gauge) were used to measure the temperature of gases leaving the combustion chamber as they entered the first pass. Thermocouples of copper and constantan wire (22 B. & S. gauge) were used to measure the temperatures of the gases leaving the

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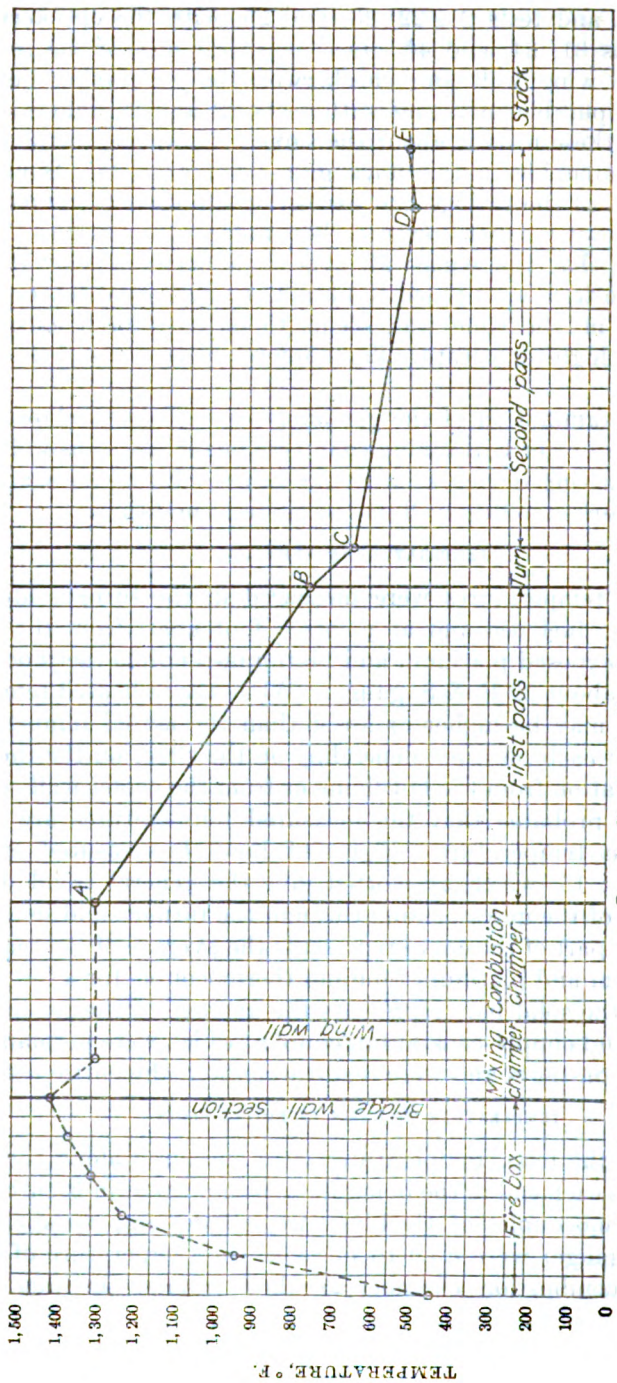

FIGURE 14.—Variations of temperature over fuel bed and along the path of the gases from the combustion chamber to the breeching, taken in test 15

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first pass, entering and leaving the second pass, and in the stack. Four thermocouples were used at each position, *A*, *B*, *C*, *D*, and *E*. (figs. 2 and 3)—one thermocouple being placed in the center of each individual flue on the left-hand side of the boiler in all of the tests, and in all flues for tests 15, 16, 23, and 25, when 32 thermocouples were used. In the boiler uptake the temperatures of flue gases were measured by four thermocouples set 3½ inches in from the metal casing, as indicated in Figures 1, 2, and 3. In this manner the average temperatures were ascertained. These varied considerably, and demonstrated how the readings based on a single couple may be high or low, and how necessary it is to exercise care in the measurement and sampling of gases flowing in stream lines. Table 4 gives the averages of temperature readings of the thermocouples at various positions as well as the averages for each test, and shows the effect of leakage of hot gases as well as infiltration of air at the joints of the furnace sections.

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TABLE 4.—*Temperatures measured along the path of the gases, °F.*

Test	Side of boiler	Fuel	Position of thermocouples*																								
			A					*B*					*C*					*D*					Flue gas				
			1	2	3	4	Average	1	2	3	4	Average	5	6	7	8	Average	5	6	7	8	Average	1	2	3	4	Average
3	L	Pittsburgh coal	------	------	------	------	------	962	------	------	------	962	905	------	866	------	886	670	636	584	------	630	699	632	670	717	682
2	L		------	------	------	1,511	1,511	1,020	937	1,022	930	977	883	873	853	888	874	612	615	------	564	597	675	605	603	643	632
21	L		------	1,292	------	------	1,292	710	838	704	------	751	------	621	605	493	573	515	518	500	621	539	538	527	474	503	512
21	R		------	1,292	------	1,199	1,246	771	783	752	697	751	663	673	608	598	636	538	518	378	487	480					
22	L		1,427	1,177	------	------	1,302	965	957	882	962	942	843	879	734	840	824	706	709	643	691	687	737	650	667	718	694
22	R		1,495	------	------	1,355	1,425	941	899	912	871	907	758	876	754	786	794	718	706	633	637	673					
25	L		1,464	1,541	1,442	------	1,482	976	1,010	979	912	969	862	909	786	871	857	706	667	538	679	648	752	703	697	874	758
25	R		1,480	1,541	1,437	------	1,486	923	997	994	918	958	803	------	829	697	776	893	706	827	643	767					
23	L		------	------	------	------	------	1,098	1,085	1,034	1,170	1,097	951	1,012	821	------	928	792	896	734	835	814	943	772	673	935	832
23	R		------	1,804	1,657	------	1,731	1,063	1,194	1,144	1,050	1,088	1,039	918	887	860	926	986	887	896	772	885					
5	L	Lower Kittanning coal	------	------	------	------	------	875	763	900	858	849	640	803	593	------	679	------	------	------	------	------	573	550	507	598	557
4	L		------	------	------	------	------	969	859	964	985	944	809	856	828	819	828	574	583	534	470	540	634	553	541	618	587
16	L		------	------	1,210	1,241	1,226	653	615	624	675	642	553	557	527	567	551	487	505	397	483	468	520	474	493	493	496
16	R		1,290	1,276	1,188	1,162	1,229	735	695	681	640	688	567	557	628	538	573	474	428	476	442	455					
15	L		1,366	1,383	1,157	1,249	1,289	786	786	752	739	766	681	673	596	621	643	525	553	447	505	508	573	442	474	544	507
15	R		1,375	1,348	1,263	1,192	1,295	721	752	743	724	735	583	643	688	621	634	503	479	483	444	477					
14	L		1,339	1,326	1,258	1,192	1,279	743	788	739	773	761	668	688	598	598	638	442	550	442	500	484	583	456	525	542	525
13	L		1,529	1,511	1,520	1,449	1,502	754	945	903	------	867	------	------	824	821	823	------	630	459	547	544	681	541	515	668	601
11	L		1,507	1,449	1,493	1,546	1,499	956	926	988	1,022	973	852	918	863	910	886	564	678	------	564	602	704	518	624	630	621

* For position of thermocouples, see Figures 1, 2, and 3.

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In test 25, the temperature drop from front to rear in the last pass was low; an inspection of the boiler after the test showed that some of the asbestos rope and boiler cement between the seventh and eighth sections on both sides of the boiler had dropped out, permitting some of the gases in the first pass to enter the last pass, thus raising the temperature. This condition was remedied for following tests, it is mentioned to show that the flues must be examined occasionally in order to maintain cast-iron sectional boilers in good operating condition. The upper thermocouples *E*–2 and *E*–3 (fig. 1) in the stack, in all cases gave lower readings of temperature; this indicated that there was some infiltration of cold air from the insulation covering of the boiler. Stack thermocouples *E*–1 and *E*–4 showed an increase of temperature from similar infiltration of hot gases through joints at the bottom of the gas passages.

RELATION BETWEEN TEMPERATURE DROP AND GAS FLOW

Table 5 shows the temperatures of the gases leaving the combustion chamber at *A* (fig. 2) and the average temperature leaving the boiler at *E*. Under the "Fuel" column, Pittsburgh coal is represented by P, and Lower Kittanning coal by M. Tests are arranged according to rate of gas flow in pounds per hour, therefore low rates come first, followed by higher rates.

TABLE 5.—*Temperature drop and gas flow*

Test number	Fuel [a]	Rate of steaming 1,000 B. t. u. per hour	Flue gas per hour, pounds	Excess air, per cent	Temperature at *A*, gases leaving combustion chamber, °F.						Flue-gas temperature, °F.	Drop in temperature, A to stack, °F.	Drop in temp. per mean degree temp. diff., °F.
					Side of boiler	Position of thermocouples [b]				Mean			
						1	2	3	4				
21	P	1,289	2,118	52	L	-------	1,292	-------	-------	1,261	512	749	1.27
					R	-------	1,292	-------	1,199				
22	P	1,906	3,638	75	L	1,427	1,177	-------	-------	1,364	694	670	0.89
					R	1,495	-------	-------	1,355				
25	P	2,704	5,142	65	L	1,464	1,541	1,442	-------	1,484	758	726	0.86
					R	1,480	1,541	1,437	-------				
23	P	3,793	7,104	63	L	-------	-------	-------	-------	1,731	832	899	0.91
					R	-------	1,804	1,657	-------				
16	M	1,391	3,390	136	L	-------	-------	1,210	1,241	1,228	496	732	1.32
					R	1,290	1,276	1,188	1,162				
15	M	1,969	5,569	154	L	1,366	1,383	1,157	1,249	1,292	507	785	1.32
					R	1,375	1,348	1,263	1,192				
14	M	2,172	5,443	142	L	1,339	1,326	1,258	1,192	1,279	525	754	1.26
13	M	3,270	6,294	81	L	1,529	1,511	1,520	1,449	1,502	601	901	1.23
11	M	3,122	6,946	101	L	1,507	1,449	1,493	1,546	1,499	621	878	1.16

[a] P, Pittsburgh coal; M, Lower Kittanning coal.
[b] For position of thermocouples, see Figures 1 and 2.

The figures in the last column of Table 5 are calculated from the average temperature of the gases leaving the combustion chamber *A*, the average flue-gas temperature at *E*, and the steam temperature—assuming that the gas flow is constant and that the drop in temperature per unit area of heating surface passed over by the

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gases is proportional to the difference between the temperature of the gas for this area and the temperature of the steam. These results are calculated from the equation given in Technical Paper 303,[4] as $\text{Log}_e \frac{T_1-t}{T_2-t}=CS$. In this equation T_1 is the initial gas temperature, T_2 the final gas temperature, t the steam temperature, S the total heating surface, and C the drop in temperature between combustion chamber and flue, per degree temperature difference between gas and steam temperatures, per unit area of heating surface given in the last column.

Figure 15 shows the relation between points that are represented by $\text{Log}_e \frac{T_1-t}{T_2-t}$ and the weight of gases per hour flowing over the heating surfaces for the Pittsburgh and Lower Kittanning coals. The points

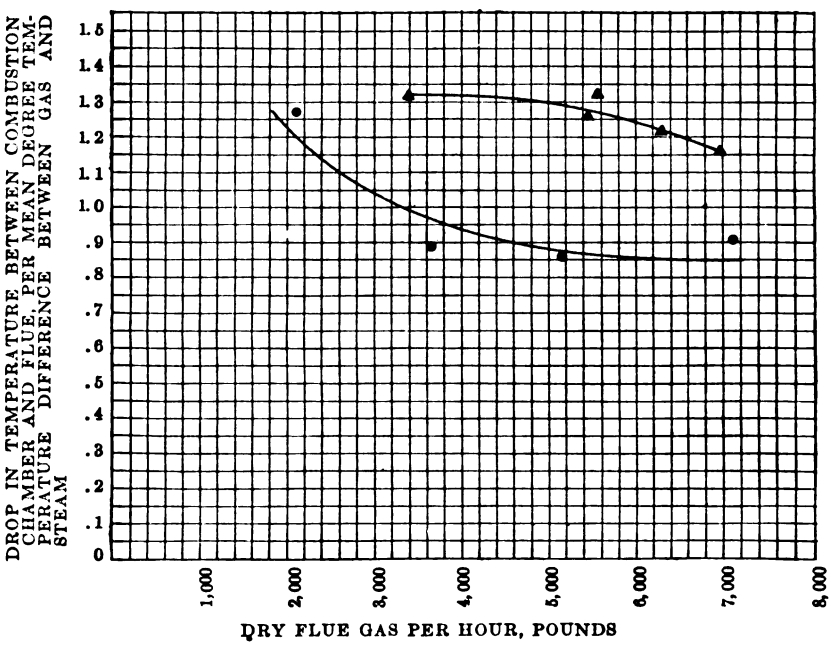

FIGURE 15.—Drop in temperature per mean degree of temperature difference of gases between combustion chamber and point of exit from boiler with weight of gases flowing: ●, Pittsburgh coal, checkerwork; ▲, Lower Kittanning coal, checkerwork.

fall along two curves, the values with Pittsburgh coal being similar to those obtained in earlier tests reported in Technical Paper 303.[5] The values plotted for Lower Kittanning coal form another curve above that for Pittsburgh coal, and show that the temperatures of the gases at the same rate of flow, from the latter fell less than those of the gases from the Lower Kittanning coal in a manner similar to the earlier tests mentioned. The higher the volatile content of

[4] Blizard, John, Neil, James, and Houghten, F. C., Value of coke, anthracite, and bituminous coal for generating steam in a low-pressure cast-iron boiler: Tech. Paper 303, Bureau of Mines, 1922, p. 38.
[5] Work cited, p. 37.

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the coal used, the smaller was the drop in temperature, as might be expected. In these tests with bituminous coal, the flue-gas temperatures tended to rise as the test progressed; this effect should be expected since a deposit of soot was constantly accumulating on the surfaces.

The smaller drops in temperature of gases passing through the boiler as shown in tests 21, 22, and 25 in the thirteenth column of Table 5 for Pittsburgh coal are believed to be due to the continued combustion of gases, tars, and soot in the boiler flues beyond the combustion chamber; this idea is further indicated by the higher exit temperatures with the Pittsburgh coal.

The lower values for Lower Kittanning coal shown in the thirteenth column, tests 16 and 14, are probably due to the high excess air in flue gases with comparatively low rate of steaming.

VELOCITY OF GASES IN PASSES AND SMOKE EXIT

The velocity of the gases at openings to the mixing chamber was not calculated but, because of the higher temperatures and smaller area of openings, must have been greater than the velocity of the gases at positions *A* in the first pass, which varied from 12 to 55 feet per second as calculated from the observations taken. At position *C* at the front of the boiler in the second pass, similar velocities were from 5 to 28 feet per second. The velocity of the gases in the smoke outlet of the boiler were from 3 to 20 feet per second.

COMPOSITION OF THE GASES IN THE COMBUSTION CHAMBER AND IN THE GASES LEAVING THE BOILER

During several tests with Lower Kittanning coal and with Pittsburgh coal, gas samples leaving the combustion chamber were collected over mercury, through water-cooled samplers, and then analyzed. Table 6 gives analyses of samples taken before and after firing. Below the report of analyses of gas taken simultaneously at the combustion chamber and in the boiler-smoke outlet are given the calculated percentages of excess air for each sample period. These results show that there was considerable infiltration of air along the path of the gases through the boiler, and that this air diluted the gas sample and lowered the temperature of the gases, especially along the top row of gas passages.

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TABLE 6.—*Composition of gases leaving the combustion chamber and flue*

Kind of fuel	Lower Kittanning coal																					
Test number	11		13		14				15				16				17					
Sampling period, start	1.40	2.00	2.18	2.43	11.00	11.20	11.40	12.00	3.20	4.20	4.40	5.00	12.40	1.05	1.30	2.00	11.00	11.20	11.40	12.00	12.20	12.40
Sampling period, close	2.00	2.20	2.40	3.05	11.18	11.40	12.00	12.20	3.40	4.40	5.00	5.20	1.00	1.30	2.00	2.30	11.20	11.40	12.00	12.20	12.40	1.00
Before or after firing, or whole period [a]			W.P.	W.P.	A.F.	B.F.	A.F.	B.F.	B.F.	A.F.	B.F.	A.F.	B.F.	A.F.	B.F.	A.F.	A.F.	B.F.	A.F.	B.F.	A.F.	B.F.
Coal fired per hour, pounds	337	337	343	343	229	229	229	229	224	224	224	224	150	150	150	150	225	225	225	225	225	225
Flue-gas temperature, °F	678	603	587	580	493	507	520	525	580	474	500	547	503	505	500	518	589	564	564	560	557	550
Combustion chamber gases, per cent:																						
CO_2	10.7	11.7	8.8	11.5	12.7	13.0	14.1	12.1	8.0	7.5	10.8	6.5	14.5	10.0	11.3	9.9	12.9	15.8	9.5	15.5	10.7	12.6
O_2	8.4	7.6	10.0	7.6	6.9	6.6	4.6	8.0	11.5	11.6	9.2	14.1	4.6	9.3	8.1	8.2	7.0	4.4	10.3	4.4	8.8	6.9
CO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.8	0.0	0.0
CH_4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
H_2	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N_2	80.9	80.7	81.2	80.9	80.0	80.4	81.3	79.9	80.3	80.1	80.0	79.4	80.9	80.7	80.6	81.9	80.1	79.5	80.2	79.3	80.5	80.3
Flue gases, per cent:																						
CO_2	9.5	9.5	8.7	8.9	8.4	8.5	9.2	8.4	5.7	5.2	8.3	5.3	10.0	6.8	7.6	7.0	10.3	11.0	8.3	12.2	7.7	10.3
O_2	10.2	10.1	11.4	10.3	11.3	11.4	10.6	11.4	14.3	14.5	11.7	15.1	9.9	13.2	12.5	12.8	8.8	7.5	10.7	7.8	11.5	9.3
CO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.2	0.0	0.2	0.0	0.0
N_2	80.3	80.4	79.9	80.8	80.3	80.1	80.2	80.2	80.0	80.3	80.0	79.6	80.0	80.0	79.9	80.2	80.9	81.3	81.0	79.8	80.8	80.4
Excess air, per cent:																						
Combustion chamber	65.0	55.0	87.0	55.0	48.0	45.0	27.0	61.0	110.0	103.0	77.0	205.0	27.0	77.0	61.0	61.0	50.0	25.0	95.0	24.0	71.0	44.0
Flue gas	93.0	91.0	117.0	93.0	114.0	117.0	100.0	116.0	209.0	216.0	124.0	254.0	88.0	166.0	145.0	152.0	70.0	53.0	100.0	58.0	117.0	78.0
Difference	28.0	36.0	30.0	38.0	66.0	72.0	73.0	55.0	99.0	113.0	47.0	49.0	61.0	89.0	84.0	91.0	20.0	28.0	5.0	34.0	46.0	34.0
Per cent of heat of fuel in gases:																						
Combustion chamber	0	0	0	0	1.9	0	0	0	4.4	10.4	0	0	0	0	0	0	0	1.1	0	2.8	0	2.8
Flue gas	0	0	0	0	0	0	0	0	0	0	0	0	0.6	0	0	0	0	1.0	0	0.9	0	0

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Kind of fuel	Lower Kittanning coal														Pittsburgh coal		
Test number	18					19			20						23		
Sampling period, start	1.00	1.20	1.40	2.00	2.20	12.00	12.20	12.40	12.40	1.00	1.20	1.40	2.00	2.20	1.00	1.20	1.40
Sampling period, close	1.20	1.40	2.00	2.20	2.40	12.20	12.40	1.00	1.00	1.20	1.40	2.00	2.20	2.40	1.10	1.40	2.00
Before or after firing, or whole period[a]	A. F.	B. F.	A. F.	B. F.	A. F.	B. F.	A. F.	B. F.	A. F.	B. F.	A. F.	B. F.	A. F.	B. F.	A. F.	W. P.	W. P.
Coal fired per hour, pounds	225	225	225	225	225	225	225	225	225	225	225	225	225	225	429	429	429
Flue-gas temperature, °F	573	541	550	553	544	560	579	527	576	618	648	688	663	598	855	865	870
Combustion chamber gases, per cent:																	
CO_2	8.6	12.4	13.1	12.5	8.9	12.5	13.8	14.6	15.6	16.4	15.3	16.8	15.7	13.7	16.0	16.2	15.5
O_2	10.5	7.3	5.2	7.7	10.3	6.7	5.2	6.4	1.5	2.0	1.5	2.1	0.4	2.7	1.8	1.3	3.2
CO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4	2.6	3.1	1.0	3.8	1.0	0.4	1.2	0.3
CH_4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.0	0.1	0.0	0.0
H_2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.0	1.0	0.1	0.9	0.1	0.0	0.4	0.0
N_2	80.9	80.3	81.7	79.8	80.8	80.8	81.0	79.0	79.6	79.0	79.0	79.9	79.0	82.5	81.7	80.9	81.0
Flue gases, per cent:																	
CO_2	7.6	9.7	9.4	10.0	6.4	10.7	10.2	7.2	11.9	12.6	12.3	12.7	12.7	12.4	11.5	11.3	11.8
O_2	12.0	10.1	9.9	10.1	13.2	9.3	8.4	12.9	6.3	6.5	5.9	6.5	5.3	7.4	7.7	7.3	7.5
CO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.1	0.5	0.1	1.0	0.0	0.3	0.7	0.2
N_2	80.4	80.2	80.7	79.9	80.4	80.0	81.4	79.9	81.0	80.8	81.3	80.7	81.0	80.2	80.5	80.7	80.5
Excess air, per cent:																	
Combustion chamber	96.0	52.0	32.0	58.0	93.0	46.0	32.0	44.0	−1.0	3.0	−3.0	7.0	−10.0	11.0	7.0	2.0	17.0
Flue gas	130.0	91.0	87.0	92.0	164.0	79.0	64.0	157.0	38.0	44.0	36.0	44.0	29.0	54.0	55.0	48.0	53.0
Difference	34.0	39.0	55.0	34.0	71.0	33.0	32.0	113.0	39.0	41.0	39.0	37.0	39.0	43.0	48.0	46.0	36.0
Per cent of heat of fuel in gases:																	
Combustion chamber	0	0	0	0	0	0	0	0	10.5	7.8	13.7	4.5	15.5	4.3	2.4	5.2	1.1
Flue gas	0	0	0	0	0	0	0	0	3.6	0.5	2.2	0.5	4.2	0	1.4	3.3	0.9

[a] W. P.=whole period; B. F.=before firing; A. F.=after firing.

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UNDEVELOPED HEAT AND COMBUSTIBLE

In test 15, at 73 per cent of boiler rating, with checker brickwork between the mixing and combustion chambers, one sample taken in the combustion chamber before firing showed over 4 per cent of the heat in the coal was undeveloped there; but a corresponding sample taken at the boiler outlet showed no combustible gases because of the high increase of excess air and the combustion in the flues. The next sample, taken after firing, showed 10.4 per cent undeveloped heat in combustion-chamber gases, and similarly no combustible in the flue gas and even a greater increase of excess air between the two points. All samples showed that there was air leakage along the boiler flues, and the amount of excess air was increased from 5 to as much as 113 per cent between the two points of sampling. In the series of tests covered by this report no gas samples were taken in the furnace or in front of the brickwork wall in the combustion chamber. Tests made earlier showed that combustible gases would be accompanied by some tar and soot, but neither of these was determined in these tests; therefore the total undeveloped heat in gases would be higher than the values given at the bottom of Table 6. However, the combustible gases give an indication of the amount of the undeveloped heat at each point of sampling.

Special tests 17 and 18, with Lower Kittanning coal, were run only for gas analysis and smoke observations, at about 75 per cent of boiler rating. Table 7 gives general data for these tests. Test 17 was fired by the "center" method and test 18 by the spreading method, both having checkerwork wall. In each test especial care was taken, by closing the joints around the cleaning doors with asbestos cement, to reduce infiltration of air. The sealing of the front cleaning-door joints must have helped materially when the packing cement was first applied, because the air excess in one sample taken after firing was increased by 5 per cent only between the combustion chamber and flue outlet. In later samples, as the cement loosened and cracked, the infiltration after firing increased to as high as 71 per cent during the same day's run. As the increased excess air admitted at the cleaning doors is heated up from room temperature to the flue-gas temperature, the increased loss may be considerable. Tight door joints help to cut down this loss.

The coking method was used for the first firing in test 17. Analyses showed greater combustible in gases leaving the combustion chamber and at the flue outlet than when the spreading method was used in later firings when no combustible whatever was detected at either point of sampling; moreover, no greater air excess was required although 15 minutes after firing and 10 minutes before the next firing the fire was raked to cover holes in the fuel bed.

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TABLE 7.—*General data on special tests 17 to 20* [a]

Kind of coal	Lower Kittanning			
Number of trial	17	18	19	20
Duration of trial, hours	2	2	2	2
Interval between firings, minutes	40	40	40	40
Fuel fired each firing, pounds	150	150	[b] 167	150
Thickness of fuel bed, inches	8	8	8	12
Drafts, inches of water:				
In ash pit			0.02	0.01
In furnace (front)			.19	.25
In furnace (rear)			.22	.27
In combustion chamber			.35	.38
In stack	0.69	0.64	.61	.62
Rating, per cent developed	75	75	75	75
Smoke, per cent of black	9	7	9	13
Air admitted over fire	No.	Yes.	No.	No.
Method of firing	Center, at 11.40; spreading, at 12.20.	Spreading.	Spreading.	Spreading.

[a] For gas analysis refer to Table 6.
[b] Coal fired at 11.40, 200 pounds; at 12.20, 150 pounds.

EXCESS AIR

In test 18 during the first firing period air was admitted over the fire through sliding air shutters on the firing doors. The spreading method of firing was used, and the fuel bed was raked 15 minutes and 30 minutes after firing. For the second firing period, 40 minutes after the first firing, the air slides in firing doors were closed for 20 minutes, then opened halfway for the following 20 minutes, or the last half of the firing period just before the third firing. The excess air was 25 per cent higher in the sample taken in the combustion chamber during the second half of this second firing period, but the excess air in the flue gas leaving the boiler was about the same for both samples. The high excess air in the sample taken at the fifth firing was probably due to the leakage of air around cleaning doors and at the furnace-door air openings.

Tests 19 and 20 were run with Lower Kittanning coal, the spreading method of firing fuel beds respectively 8 and 12 inches thick, and the checkerwork wall in the combustion chamber. Although the joints around the front cleaning doors and openings in firing doors were sealed with asbestos cement, this precaution did not serve to keep down the excess air at the flue outlet in test 20 which was run with the thicker fuel bed; in this test, with the same stack draft, the draft over the fire was higher because of the added resistance to air flowing through the thick fuel bed.

Samples taken during test 19 showed no combustible gases leaving the combustion chamber or at the flue outlet. In test 20, run with the 12-inch fuel bed, all samples showed unburned combustible in the gases. The undeveloped heat in gases leaving combustion chamber after firing was 10.5, 13.7, and 15.5 per cent of the heat in the coal, giving an average of 13.3 per cent caused by deficient air supply. Corresponding values in stack samples showed an average

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of 3.3 per cent combustible due to dilution of air and combustion in the flues. The undeveloped heat in three samples of the gases leaving the combustion chamber before firing was 7.8, 4.5, and 4.3 per cent respectively—an average of 5.5 per cent. The stack samples contained 0.5 and 0.0 per cent combustible, or an average of 0.3 per cent of the heat in the coal leaving the boiler as unburned gases. These results indicate that the excess air supply over the fuel bed should be about 30 per cent in order to avoid unburned combustible in the gases leaving the combustion chamber, even with the brick checkerwork wall used for mixing the air and gases.

During test 23, run at 139 per cent rating with Pittsburgh coal and with checkerwork wall, some samples were taken of gases leaving the combustion chamber for comparison with samples taken at the same time in the smoke-flue outlet of the boiler. These samples showed a low excess of air in the flue gases leaving the boiler because of leakage between sections and at the cleaning doors. In this test the air slides in the firing door and the shutters or air doors were kept wide open for 3 minutes after firing or raking; then they were left "cracked" or open 1 inch for 5 minutes before they were closed, and were kept so until the next raking, which was 2 minutes before a firing. In this test combustible kept appearing in the flue gases leaving the boiler, therefore this rating apparently represents about the limit at which the boiler should be operated to get reasonably complete combustion with Pittsburgh coal.

SMOKE

The density of the smoke leaving the chimney was estimated by comparison with a Ringelman smoke chart. Readings were taken at 15-second intervals for two or more firing periods when conditions of the fire were fairly representative. The same method of firing was used in all the smoke tests with bituminous coal; but there was variation in the time of admitting air over the fuel bed after firing or raking.

The percentage of black smoke given in the last column of Table 8 was computed from these smoke readings by the formula:

$$\frac{\text{Sum of readings}}{\text{Number of readings} \times 5} \times 100 = \text{per cent of black smoke.}$$

More smoke was made immediately after raking or cradling the fuel bed to prepare it for the firing than was made after the firing. The figures in the last column of Table 8 indicate that Pittsburgh coal made more smoke in all tests than did the Lower Kittanning coal at similar ratings.

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TABLE 8.—*Smoke readings*

Test No.	Fuel	Rate of firing, pounds per hour	Coal per firing, pounds	Average interval between firings, minutes	Flue gas temperature, °F.	CO_2, per cent	CO, per cent	Excess air, per cent	Duration of smoke readings, minutes	Fire-door air-ports all open after firing, minutes	Smoke, black, per cent
3	Pittsburgh coal	247	124	30	682	11.0	0.2	62	300	4	14
2		314	167	32	652	10.3	.1	74	250	2	9
21		140	150	64	512	11.6	.4	52	242	30	21
22		211	151	43	691	10.3	.2	75	204	10	9
25		300	150	30	758	10.5	.4	65	121	5	23
23		429	150	21	832	10.9	.4	63	194	3	21
7	Lower Kittanning coal.	160	157	59	530	9.7	.1	88	159	2	5
26		231	154	40	526	6.2	.0	193	152	3	8
6		235	157	40	559	8.3	.0	117	181	2	9
5		244	163	40	557	7.9	.0	129	201	2	7
4		299	154	31	587	9.1	.1	101	200	2	8
8		352	82	14	615	8.9	.1	101	95	2	11
16		150	150	60	496	7.7	.0	136	62	2	3
15		224	153	41	507	7.0	.0	154	88	2	6
14		229	153	40	525	7.6	.1	142	69	2	6

Test 12 was a short test run at about 50 per cent rating with Lower Kittanning coal for smoke observations; and neither wing walls nor checkerwork were used in the combustion chamber. The average percentage of CO_2 was 8.9; of O_2, 10.9; no CO. The flue-gas temperature was 500° F. The resulting smoke readings indicated 13 per cent of black smoke. By comparing this test with test 7, which was run with a slot wing wall and showed only 5 per cent of black smoke, it appears that the wing wall helped materially to reduce smoke when this fuel was burned.

Figure 16 indicates the smoke record for test 4, and shows the effect of raking and firing.

CLINKERING

None of the three fuels gave excessive trouble from clinkering, but the coke, with its higher ash content, made more clinkers than the other two fuels. The percentages of total refuse removed as clinker were as follows: Pittsburgh coal, 25 to 50 per cent; coke, 50 to 67 per cent; Lower Kittanning coal, 20 to 43 per cent. The higher percentages of clinker accompanied the higher rates of burning with all three fuels. The clinkers from coke stuck close to the grate bars and were somewhat more difficult to remove than clinkers from the other two fuels; consequently, in burning coke it was necessary to clean the fire more often.

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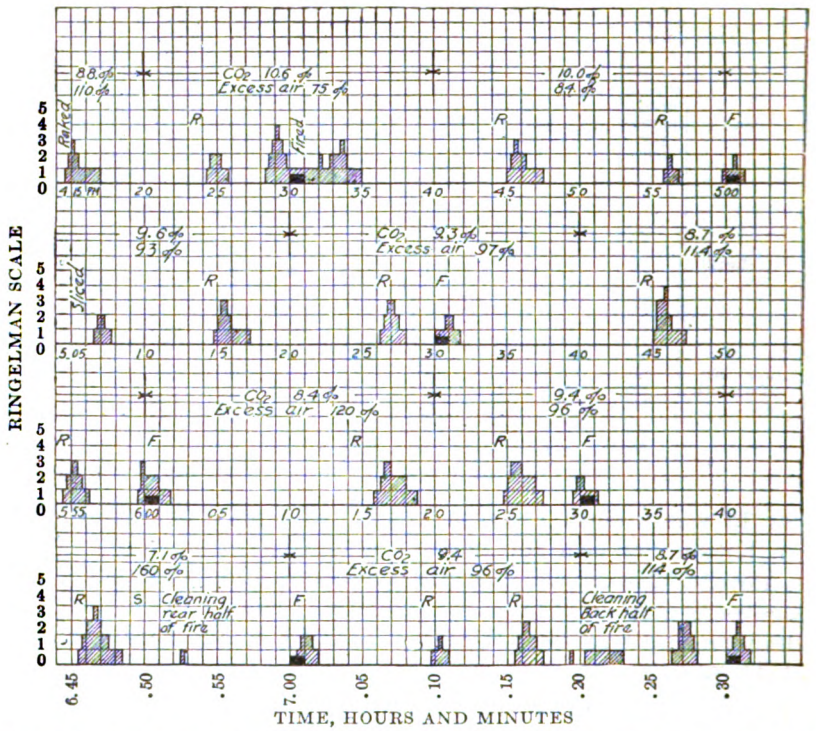

FIGURE 16.—Smoke record for test 4, firing Lower Kittanning coal by coking method: *F*, Fired; *R*, raked; *S*, sliced

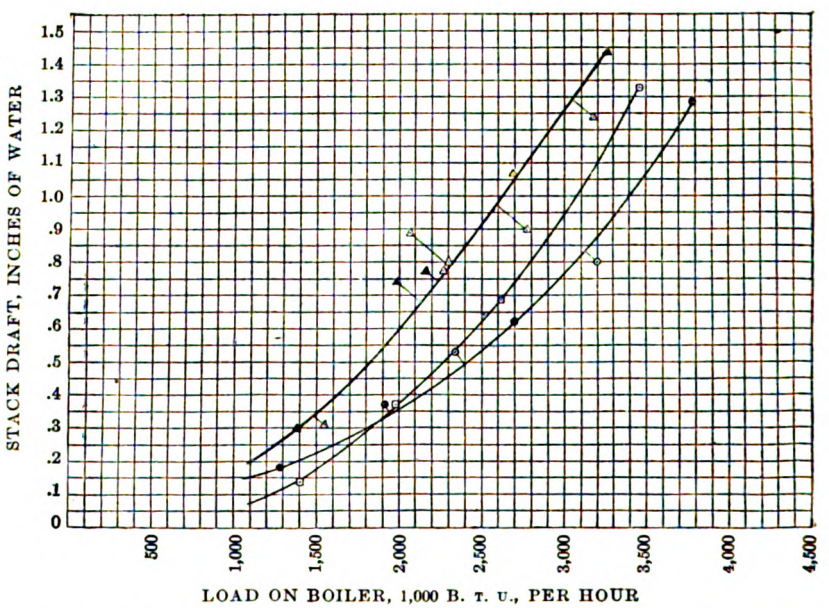

FIGURE 17.—Stack draft at different rates of steaming with the several fuels: △, Lower Kittanning coal, wing wall; ▲, Lower Kittanning coal, checkerwork; ⊙, Pittsburgh coal, wing wall; ●, Pittsburgh coal, checkerwork; ⊡, coke, no brickwork

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DRAFT REQUIRED TO BURN FUELS

TOTAL DRAFT

Figure 17 shows the draft in the flue where the gases left the boiler. The stack drafts for the Lower Kittanning coal were higher in all tests than for either Pittsburgh coal or coke. This was partly due to the fuel-bed resistance, and partly to the higher excess of air carried in the tests of Lower Kittanning coal, as indicated in Figure 12. The curve showing the drafts for coke crosses that of drafts for Pittsburgh coal at low ratings because of less excess air; and it lies nearer the curve for Lower Kittanning coal at the higher ratings, because the air supply and flue-gas temperatures were more nearly the same.

ASH-PIT DRAFT

The reduced pressure in the ash pit as given in item 24, Table 2, increases with the higher ratings; this increase would have the effect of drawing in more air over the fuel bed. The ash-pit door was kept partly closed at times.

DRAFT DROP THROUGH GRATE AND FUEL BED

Figure 18 shows the difference between the draft measured above the fuel bed and below the grates at various rates of combustion with the fuels tested.

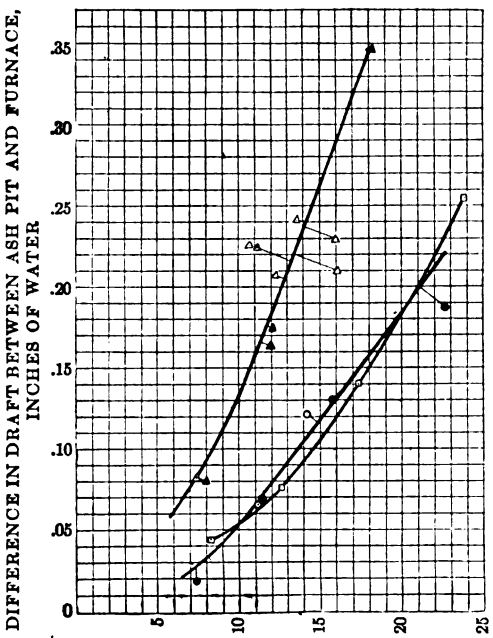

FIGURE 18.—Difference in draft between furnace and ash pit at different rates of combustion with the several fuels: △, Lower Kittanning coal, wing wall; ▲, Lower Kittanning coal, checkerwood; ⊙, Pittsburgh coal, wing wall; ●, Pittsburgh coal, checkerwork; ⊡, coke, no brickwork.

About the same draft was required to burn coke and Pittsburgh coal, and decidedly more (nearly twice as much) to burn Lower Kittanning coal at the same rate. This increase was due to the difference in the burning of coal on the grate, higher ash content and smaller size of coal, and the decided tendency of the coal to pack on the grate, thus hindering the flow of air through the fuel bed.

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DRAFT DROP BETWEEN FURNACE AND GAS EXIT FROM BOILER

Figure 19 indicates the draft needed for moving the flue gases through the mixing chamber, combustion chamber, and flues to the smoke outlet of the boiler. The quantity (pounds) of dry flue gas flowing from the boiler per hour is used as a base in plotting the

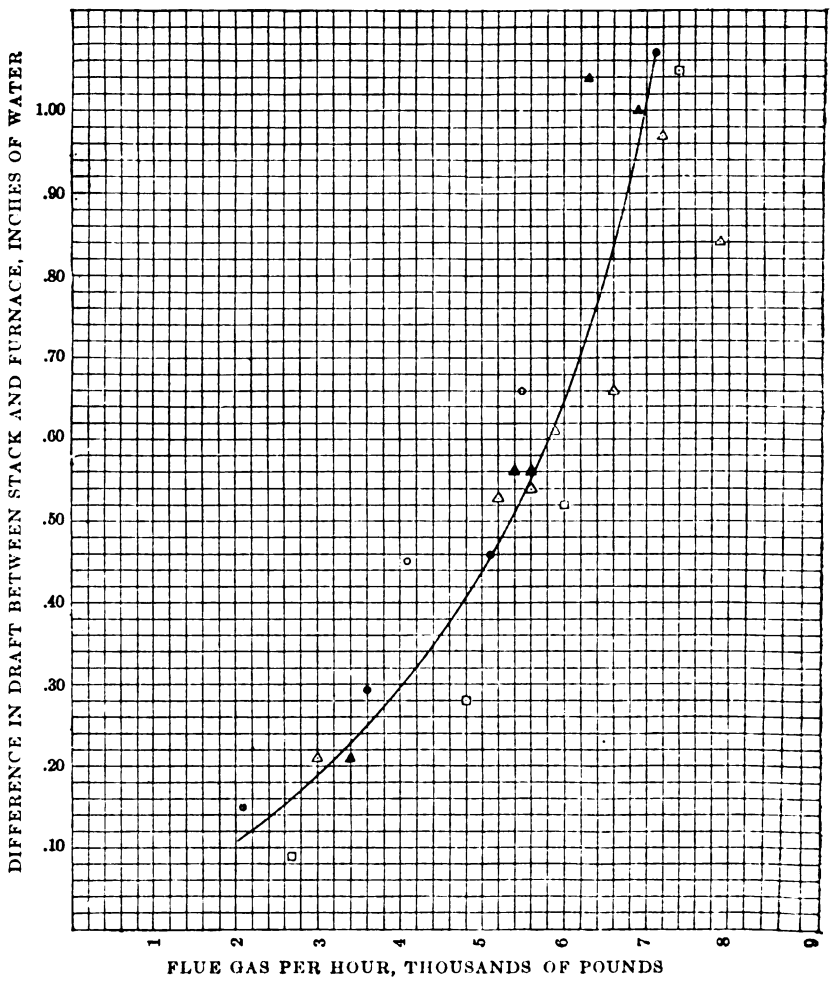

FIGURE 19.—Draft required to move flue gases from furnace through boiler to stack: △, Lower Kittanning coal, wing wall; ▲, Lower Kittanning coal, checkerwork; ○, Pittsburgh coal, wing wall; ●, Pittsburgh coal, checkerwork; ⊡, coke, no brickwork.

curve to show its relation to the difference in draft required between the furnace and the boiler exit. The drop in draft between the rear of combustion chamber and flue was about 50 per cent of the total stack draft. The drop in draft between the rear of the combustion chamber and directly over the fuel bed was about 25 per cent of the total stack draft.

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